Multi-Plane Routing Practical Applications in Future All-IP Access Networks

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Abstract

The Internet has proven to be a major contributor to the world and has had a significant impact on many aspects of our lives over the past decades. It continues to have the potential to impact societies, businesses and governments in different ways. Despite the clear significance of Internet as a key enabler of a big technological revolution, there are rising challenges associated with the exponential growth of the Internet. In addition, accelerated in part by the massive increase in devices and the capabilities of those devices, Internet traffic is increasingly becoming more dynamic and demanding. Meanwhile, users expect a quality delivery facilitated by service providers across the mobile networks from core to access.

Internet Protocol (IP) as the underlying foundation for the next-generation networks is becoming increasingly relevant considering the ubiquitous installed IP infrastructure. Correspondingly, different suggestions are being explored about the facilitation of next-generation access networks via IP mechanisms, with a growing trend towards a flat IP structure and novel topological set-ups in the backhaul. With the expected surge in global IP traffic, service providers would need to adapt accordingly to operate disruption and loss free networks supported with the developing IP infrastructure. This calls for a consistent routing optimization strategy to minimize loss in data transmission. Hence, a resilient, efficient and easily implementable routing paradigm that employs suitable Traffic Engineering (TE) techniques aligned with the developing nature of future access networks must be applied. It becomes imperative that the routing considerations for IP access networks converge with the ones found in conventional intra-domain routing.

Multi-Plane Routing (MPR) is a routing optimization approach that consolidates various aspects in an all-IP access network infrastructure and consists of both offline and online TE approaches. MPR integrates the recent multi-topology approach that leverages multiple alternative paths (for each Ingress-Egress pair) through a network that divides the physical network topology into several logical routing planes facilitating path diversity. In this thesis, MPR is extended from a practical prospective in line with the architectural evolution of access networks

and the introduction of new traffic types and applications.

The offline and online TE strategies of MPR have been modified to suit the flattened network architecture. Correspondingly, a MPR-based TE approach is proposed considering two different scenarios to reflect the evolution in the architectural design of access network structures under a realistic traffic scenario. It becomes evident that for ranges of topologies, MPR's utilization of the whole topology in building path diversity in networks, allows for significant improvement of networks' capacity, performance and support for meshing.

Moreover, with the rise of different traffic types of various nature, Quality of Service (QoS) is increasingly becoming important. Tactile Internet is considered in this thesis in addition to other traffic applications. To this end, a novel routing technique which accommodates for the strict requirements of this new traffic type in access networks architectures will be proposed. Validation of the proposed techniques through simulations have been performed and presented, illustrating the effectiveness of the proposed methods.

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List of publications

Journals:

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Conferences:

1. M. Farhoudi, P. Palantas, B. Abrishamchi, A. Mihailovic and A.H. Aghvami, "A Novel Reliable Routing Scheme for Tactile-oriented Internet Traffic," International Conference on Telecommunications (ICT), pp. 1044-1047, Limasol, 3-5 May 2017.

2. M. Farhoudi, B. Abrishamchi, A. Mihailovic and A.H. Aghvami, "A practical multi-plane routing-based traffic engineering scheme in evolutionary convergent all-IP access networks," 23rd International Conference on Telecommunications (ICT), pp. 1-6, Thessaloniki, 16-18 May 2016.

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4. B. Abrishamchi, M. Farhoudi, A. Mihailovic and A.H. Aghvami, "A Novel Minimum Set Cover Routing PlaneConstruction Approach for Random Wireless IPAccess Networks" IEEE Wireless Communications and Networking Conference (WCNC), pp. 1-6, Barcelona, 15-18 Apr. 2018.

List of abbreviations

AR	Aggregation Router
AS	Autonomous System
BGP	Border Gateway Protocol
DiffServ	Differentiated Services
ECMP	Equal Cost Multipath
eNodeB	Evolved Node B
FIB	Forwarding Information Base
GDP	Growth Domestic Product
GW	Gateway
H2H	Human to Machine
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
INP	Internet Network Provider
IntServ	Integrated Services
IP	Internet Protocol
IS-IS	Intermediate System to Intermediate System
ISP	Internet Service Providers
ITU	International Telecommunication Union
LSP	Label Switched Path
LTE	Long-Term Evolution
M2M	Machine to Machine
MLU	Maximum Link Utilisation
MPLS	Multi-Protocol Label Switching
MPR	Multi-Plane Routing
MSC	Minimum Set Cover

MT-OSPF	Multi-Topology OSPF
OSPF	Open Shortest Path First
PDI	Path Diversity Index
QMPR	QoS-aware Multi-Plane Routing
QoP	Quality of Plane-set
QoS	Quality of Service
RIB	Routing Information Base
RP	Routing Plane
RSVP	Resource Reservation Protocol
SDN	Software-Defined Networking
SLR	Service Level Requirement
TAP	Tactile Aware Policy
TCP	Transmission Control Protocol
TE	Traffic Engineering
TM	Traffic Matrix
ToS	Type of Service
VoIP	Voice Over IP

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Introduction

The Internet has evolved as an open global platform that would enable everyone, everywhere to share information, access wide ranging opportunities, and cooperate across geographic and cultural boundaries. The exponential growth of the Internet has turned it into a multi-faceted collaborative environment connecting a wide range of users. The impact of this growth is shaping the way users on different scales interact with each other as reflected in our daily lives. Accordingly, the emergence of exciting new devices along with new highly demanding applications have put even more burden on the routing fabric of the Internet in recent years. It has been predicted that there will be approximately 8.3 billion personal mobile-ready devices and around 3.3 billion M2M connections (e.g., cars' GPS systems, monitoring systems in shipping and manufacturing sectors, or medical applications recording patient health status, etc.) by 2021 [1]. Meanwhile, the evolution of cellular network generation connectivity (2G, through to 4G or LTE and 5G) has facilitated the wide expansion of advanced multimedia applications that contribute greatly to the surging mobile and Wi-Fi traffic.

In spite of the dramatic and continuous increase in the volume of bandwidth throughout the Internet, it is becoming increasingly difficult to cope with the rising traffic demands by simply over-provisioning [2]. Moreover, the surge of highly demanding devices and applications along with the rising population and increased mobility at the edges of the network, has extended the focus from core to access networks. In addition, the rise of traffic types associated with different strict Quality of Service (QoS) characteristics necessitates the Internet model's migration from the best-effort approach (where all packets are treated the same) to a QoS differentiation based model. In fact, with the the rapid rise in continuous media streaming applications such as audio and video, along with the surfacing of new traffic applications namely Tactile, QoS and ubiquitous access are becoming increasingly important.

As the nature of the Internet has evolved, there have been adaptations in the architectural setup of access networks. Correspondingly, the new intensely dense and heterogeneous access environment has motivated adjustments in the structural setup and augmentation of new interfaces in order to support the recent transformations and satisfy the gigabit-level data traffic.

Consequently, the rise of traffic volumes in association with the growing context-aware and real-time applications over the Internet along with the networks' architectural evolution call for adaptations in the networking functionalities reflected in routing protocols and topologies in support of these changes.

1.1 The Evolution of IP Access Networks

Mobile networks are confronted with the challenge of transitioning to a data centric service being capable of carrying increasingly variant types of traffic such as data, video, voice, mobile TV and forthcoming traffic types associated with Tactile applications. Correspondingly, users expect a constant quality delivery (matching the augmentation of devices' capabilities) facilitated by service providers across the mobile networks extending from core to access. This is regardless of the rising number of network devices or contending data traffic with the backdrop of limited bandwidth.

An Access networks can be defined as bounded transitional scoped administrative domains that facilitate access to terminals (e.g. subscribers) through access nodes, internal communication between access nodes and access towards the big Internet through the aggregate Gateway.

Access network and its definition has evolved in concert with transformations in networking protocols aligned with the developing 5G concepts. IP access networks' concepts were first associated with Internet access networks (namely campus environments or ISP providers with wired or wireless access). Early cellular networks initially had very limited IP routing capabilities and did not support IP traffic. Gradually, IP access network architectures were envisaged at the time of early generation cellular access technologies [3] in conjunction with their associated packet forwarding functionalists [4]. Thenceforth, cellular and IP networks have increasingly converged at the edges of networks to represent IP access networks. IP is now the dominant inter-networking protocol and there have been growing trends towards all-IP networks. To this end, emerging access networks can utilize the ubiquitous IP infrastructure [5,6]. This translates into an extended adoption of native IP protocols leading to the convergence of core and access networks, hence facilitating a more uniform network wide communication [7].

Correspondingly, with the expected surge in the global IP traffic aligned with the rapid rise in IP-based applications combined with faster radio access technologies throughout the Internet, there has been an adoption of open IP interfaces in the integrated evolutionary backhaul network designs [8, 9]. This is indicative of the cellular wired backhaul and Internet access based network designs converging on the IP-based infrastructure model. Henceforth, this design space will be referred to as all-IP access networks which are positioned at the edges of the Internet routing fabric.

The expected trends towards heterogeneous wireless access networks could also have a significant impact on the evolutionary deployment of access networks. To this end, it is envisioned that access networks with structural properties correspondent to the required heterogeneous oriented capacity pertaining to macro-, femto- and micro-cell access points will emerge.

1.2 Routing Challenges in Evolutionary Access Networks

The exponentially increasing density and changing dynamics in Internet traffic has put a burden on the Internet networks extending to access networks. Correspondingly, users with various QoS demands expect a decent service delivery across both wireless and wired networks. Currently, most access networks use Multi-Protocol Label Switching (MPLS) [10] which delivers services over a dedicated single infrastructure through creating Labelled Switched Paths (LSPs). In MPLS, the scalability and robustness become an issue due to the complexity and overhead associated with building and maintaining LSPs to which flows are mapped and the extra information added to each packet [2].

Open Shortest Path First (OSPF) [11] is a commonly used intra-domain dynamic link-state IP protocol. OSPF is scalable and robust against element failures but does not support arbitrary traffic splitting as opposed to MPLS. In addition, OSPF does not facilitate efficient path diversity as path alterations could be timely due to the required update of link weights and retransmission of the corresponding changes across the network.

Equal-Cost Multi-Path (ECMP) [12] which was initially adopted and evaluated in [13] is an add-on option of OSPF. ECMP facilitates the equal splitting of traffic which is not sufficient for near-optimal performance as compared to MPLS as optimal routing generally requires arbitrary splitting of traffic [2]. ECMP is highly intractable in case of diverse and random topologies for numerous cases of sources and destinations and even the best setting of the weights can diverge considerably from optimal [14, 15].

In addition, the exponential rise of Internet traffic associated with different strict QoS requirements has augmented routing challenges in access networks and has increasingly enforced the adoption of QoS-aware policies accordingly. As an example, users expect their laptops and other portable communication devices to deliver wide-ranging real-time services such as Video over IP, VOIP, video conferencing and media streaming, hence demanding strict QoS guarantees from the underlying network. Moreover, the surfacing of new application types namely Tactile applications, demand more innovative approaches to be integrated in order to address the specific stringent requirements. In fact, research in the area of future wired and wireless access networks has been identified as being essential for the Tactile Internet [16]. Additionally, the architectural evolution of access networks calls for consistent adaptations to routing approaches within such domains.

Another significant consideration is the increasingly relevant traffic distribution break down in access networks. Correspondingly, there has been a surge in traffic locality in access networks whereas the outgoing traffic is still highly prevalent considering the nature of the Internet applications. Therefore, the routing optimization techniques must take into account the fluctuating balance between internal/external traffic in order to represent a viable solution in future access networks.

Multi-plane Routing (MPR) is a purely IP-based solution and was initially introduced in [17]. MPR which integrates multiple instances of OSPF paths in its approach to facilitate path diversity, aims to address the deficiencies associated with MPLS and ECMP and present a comprehensive solution for routing in future all-IP access networks. In this research, MPR is extended in order to address its limitations in line with the practical aspects that are discussed throughout this thesis and form the foundations of this work. MPR is discussed and presented in further detail in Section 2.5.

1.3 Thesis Contribution

In this thesis, new insights into 5G features along with the evolutionary all-IP access networks have been investigated. To this end, MPR is extended through the consideration of various practical aspects namely the architectural evolution of access networks and the surfacing of new traffic applications (as detailed below). The preceding subsections (i.e. 1.1 and 1.2) have briefly outlined the key challenges in the evolutionary all-IP access networks underpinning this thesis's contributions. These underlying challenges will be elaborated on further in the next chapter. It is notable that each chapter includes an outline of its specific contributions.

Here, the entire contributions of the thesis are summarized as followed:

- MPR's offline Routing Plane (RP) construction problem (in intra-domain networks) is proven as being the generalization of the minimum set cover problem which is NP and also NP-complete. This justifies the adoption of heuristics to solve such a problem.

- The previously studied RP structure is restricted to 3G environment's architecture where the entire traffic traverses the core (i.e. gateway). MPR's model is expanded to converge the Internet routing and future cellular systems requirements by modifying the RP structure, allowing for direct communication between the Aggregation Routers (ARs). To this end, the extent of paths' construction in each logical topology is initially investigated by adding direct paths between ARs in the reference topologies, using three heuristic offline RP construction methods. Hop-count constraint is then introduced as a constraint in each RP which embodies an investigative parameter for finding the best configuration based on the number of RPs. A method for assessing the quality of logical topologies (Quality of Plane-set (QoP)) is also proposed.

- Optimization frameworks that formally characterize the offline and online TE mechanisms of MPR are presented. First, by leveraging the initial offline TE model for multi-topology construction [18] that was built upon in the initial MPR [17], our approaches to the offline TE in [19] and [20] are combined to enable hop-constrained path diversity. In addition, since increased pairings of traffic sources and sinks are considered, a corresponding new online TE model based on a multicommodity flow problem in association with different classes of flow demands is designed.

- A thorough performance analysis of MPR is conducted that investigates: i) a diverse set of topologies and meshings; ii) realistic traffic scenarios with fluctuating ratios of internal and external traffic; iii) traffic of both uplink and downlink nature where all the ARs and the GW can be *Ingress/Egress*. This expands upon the performance analysis of [20] where a single topology was examined, hence rendering novel and more concrete conclusions in comparison with the initial evaluations of the early versions of MPR [21] (i.e. referred to as the GW anchored traffic distribution scenario). To the best of our knowledge, such a thorough practical analysis that facilitates a comprehensive vision of the network's performance is absent in literature. The application of such an analytical strategy for the study of other load balancing approaches is recommended as a conclusion.

- Analyses of MPR is considered in Case I alongside Case II that reinforces the practicality of this study. This looks forth to the architectural evolution of cellular and Internet-based access networks with the aim of identifying the case with superior performance. To the best of our knowledge, despite existing research having investigated the underlying standards that support flat-IP, the validity of such a design concept has not been studied previously. To this end, the emerging utilisation of such IP-enabled direct communication is accommodated in this study.

- MPR's offline and online TE approaches are compared against that of MPLS which acts as its main rival in access network structures. It is demonstrated that the MPR-based approach outperforms the offline MPLS LSP construction method. In this context, the reliability of the aforementioned approaches is also evaluated.

- Finally, a reliable novel routing policy to accommodate haptics communication using delay, jitter and packet loss, alongside capacity, as combined path selection criteria, has been proposed. To the best of our knowledge, such a policy that is aimed at handling Tactile packets subject to the strict and multiple perquisites is absent in literature where most of the solutions for expedited routing (either best-effort or multi-path) reduce the objective to a convoluted cost or apply reductions to one or a few criteria that are selected as being pertinent. The proposed policy is based on MPR that has been remodelled to facilitate a reliable communication for Tactile packets by allowing for two types of queues to be installed in routers, for priority and non-priority traffic, respectively. Correspondingly, a consistent mathematical model has been presented.

1.4 Thesis Organisation

A chapter-by-chapter description of the thesis outline is presented as follows:

In Chapter 2, the preliminaries and related work are presented. This chapter aims to provide a literature review that elaborates on the thesis background in different aspects along with related research.

Chapter 3 presents a new approach in the offline construction of RPs across various topologies in consideration of the architectural evolution of all-IP access networks. This chapter is focused on the offline TE approach.

The practical aspects of MPR's application in future access networks is studied in detail in Chapter 4. To this end, IP TE-based MPR has been remodelled to suit the future all-IP access network structure through the extension and modification of both offline and online TE approaches.

The Tactile Internet is studied in Chapter 5. In this chapter, a novel reliable MPR-based routing approach is proposed in order to accommodate for the strictly reliable communications criteria for this traffic application.

The last chapter presents the conclusions of the thesis and contains a discussion of topics for future work as possible extensions of current research.

2

Preliminaries and Related Work

2.1 All-IP Access Networks' Architecture

Significant changes in the networks' traffic dynamics, in line with the introduction of new technologies into the market, have always triggered the design reconsideration of the existing architectures. To this end, it is currently essential for access networks to become extremely application aware and dynamic. Correspondingly, the interface and structural setup of access networks have been increasingly considered as such networks have transformed, aligned with the changes in networking aspects and the developing 5G concepts.

Meshed tree topologies are considered to be the most popular for access networks due to their simplicity and cost-effectiveness [22]. Moreover, larger numbers of base stations and increasing bandwidth demand from their radio access networks will motivate operators to replace the commonly used star based topology with a tree-topology [23]. Consequently, with the rapid growth of more reliable and high bandwidth transmission technologies, the tree based topologies for access networks are increasingly being favored [22]. In the following subsections, important emerging aspects that should be considered and catered for in evolutionary all-IP access networks will be discussed.

2.1.1 Emerging Convergence and Flat-IP

As hinted earlier, there is a growing convergence between the cellular wired backhaul and Internet access based network designs in the IP-based infrastructure model. In addition, it is envisioned that the 5G architecture will facilitate an integrated means for convergent fixed-mobile networking. To this end, operators will be able to provide for fixed and mobile users' access. Ethernet's application is expected to evolve to become a common transport platform, permitting for the integration of new and existing transmission technologies. The fixed-mobile convergence allows for the mobile networks to reuse the existing infrastructure aligned with the growing adoption of 5G [24].

Correspondingly, there have been suggestions about the next-generation IP networks' architectural design. One is the base station router products interconnected by IP, deployed in a flat user-plane architecture, with services provisioned and managed by the control plane. In such architectures, control is distributed among the access nodes. The growing trends towards standardization and a strive for flatter network architectures was discussed in [25]. This type of design is reflected in Long-Term Evolution (LTE) standardization and is also being considered in the future LTE advanced architecture [26]. With the disposal of the hierarchical network structure and flattening of the network architecture in LTE and LTE advanced infrastructure design, the access and core networks are moving toward a flat all-IP network architecture. The flat all-IP architecture also aims to reduce the number of functional network elements in comparison with previous generations [26].

In the flat architecture, base stations named evolved Node B (eNodeB) are positioned in a flat setup facilitating the distribution of radio and handover control functionalities as well as direct logical interfaces for inter-eNodeBs communications in Evolved Universal Terrestrial Radio Access (EUTRA) [27]. However, such a flat structure was initially planned for the traffic forwarding between neighboring eNodeBs to be only briefly permitted during handovers, with traffic anchoring functionalities remaining centralized in the core network [28]. Correspondingly, the associated interfaces were to be rarely activated in backhaul environments.

As the potential benefits and efficiencies of the flat structure are being realized, it is envisioned that such a structure can facilitate improved latency and reduced network load [29]. Hence, the flat structure is expected to be increasingly deployed for traffic management in addition to signalling support.

2.1.2 Constrained Capacity Heterogeneity

Another underlying issue that should be considered is the trend towards heterogeneous architectures. The overall vision for 5G entails a converged heterogeneous network environment combining a variety of wired and wireless solutions in order to interconnect a huge number of disparate end-devices and users [24]. In the envisioned 5G HetHetNets [30], the assumption of backhaul connections with unlimited capacity is very optimistic. In particular, the envisioned femtocells and picocells will potentially have backhaul connections with constrained capacity. In Figure 2.1 [30], a sample three tier HetHetNet with macrocells, picocells, and femtocells, which have different associated backhaul capacities, is demonstrated.

2.1.3 Traffic Distribution Breakdown

Traffic break down in access networks is of significance given the changing nature of Internet applications and the adaptive evolutionary architecture. Considering the instance of an access network with a single aggregate gateway towards the big Internet, local traffic can be defined as the internal communications within the access network (destined to an internal host) whereas the external/remote traffic represents the instance when traffic is destined to an external Internet host. With the popularity of applications such as YouTube, Netflix and mobile TV, remote traffic will still represent a high proportion of traffic in access networks [31]. However, there has been an increasing tendency towards topology-aware and latency-aware overlays contributing to an increase of traffic locality within the access network [32, 33]. Consequently, the access Internet gateway would possibly still represent a traffic hot-spot with the potential surge of traffic locality. Moreover, the potential benefits for keeping traffic local to the extent possi-

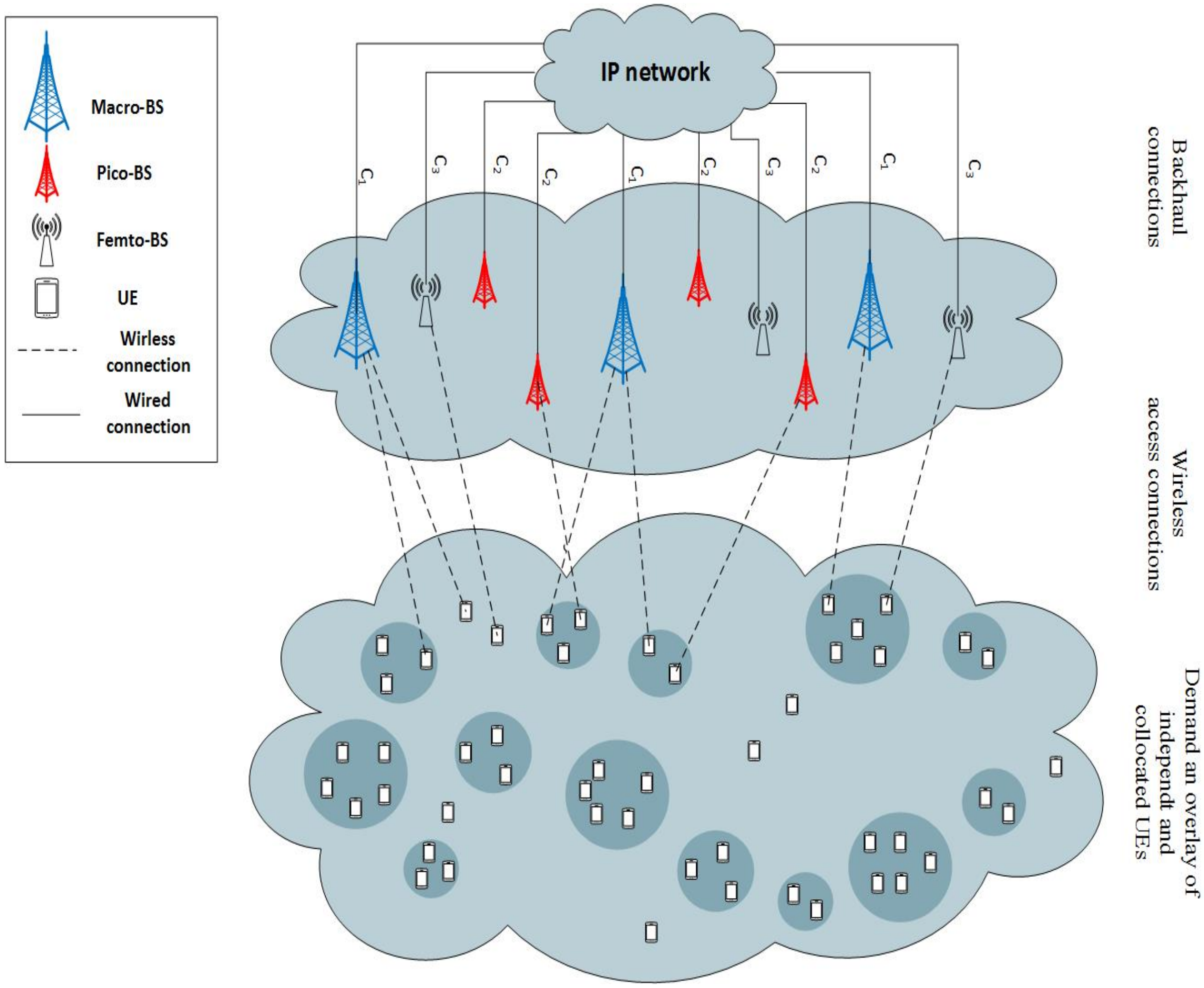


Figure 2.1: Emerging Access Network structures, a sample three-tier HetHetNet with macrocells, picocells, and femtocells, which have different backhaul capacities

ble within an access network was studied in [34] by considering how the demand is distributed between users in access networks. It is notable that the traffic distribution breakdown within every access network is different depending on user behaviours, nature of the requested popular contents, the extent of localized communications along with other specific characteristics associated with the concerning access network.

Consequent to the preceding arguments, a comprehensive study of the evolutionary access networks must take into account the varying internal/external (local/remote) traffic distribution.

2.2 Fundamentals of Traffic Engineering

Today, the Internet is still best-effort, this means that with the advent of high speed links, IP Network Providers (INPs) have increasingly adopted a bandwidth over-provisioning strategy [2]. The rising number of exciting new devices associated with the growing real-time applications over the Internet calls for a consistent transformation in the routing protocols supporting these applications. Correspondingly, it is becoming essential for cellular network operators and INPs to adopt Traffic Engineering (TE) as an indispensable tool in managing the networks' resources to meet this growing traffic demand on both inter- and intra-domain scales [2, 35].

Traffic engineering is in effect a routing optimization that aims to optimise load balancing (traffic distribution) in order to achieve a balanced capacity utilization that leads to an enhanced overall network performance. It is notable that Quality of Service (QoS) and resilience have been increasingly taken into consideration in traffic engineering [2]. This is due to many of the new traffic applications requiring extra QoS guarantees such as end-to-end delay, jitter, or packet loss in addition to bandwidth requirements. QoS protocols and new traffic types will be discussed later in this chapter. Moreover, analytical modelling applies a diversity of objective functions for traffic engineering mostly concerned with minimizing the cost of traffic distribution in the network based on conventional performance criteria (e.g. MLU, delay, throughput) [36].

There are different classes of traffic engineering applied today (i.e. Intra-domain vs. Inter-domain, IP vs. MPLS, Offline vs. Online) which will be discussed in detail in the following subsections.

2.2.1 Intra-domain versus Inter-domain

Traffic engineering is classified into intradomain and interdomain in terms of the network's scope. Intradomain TE can be described as a routing optimization approach between Autonomous System (AS) border routers (ASBRs) within one domain. Meanwhile, interdomain

TE is concerned with optimal selection of ASBRs as the ingress/egress points for interdomain traffic passing through the local AS, with the aim of network resource optimization. Figure 2.2 aims to illustrate the difference between intra- and interdomain TE semantics. In this example, the decision for communications between ASBRs B/C and E/F/K (potentially considering load balancing with interdomain multiple paths) as the egress points is the task of interdomain/outbound TE. Meanwhile, intradomain TE attempts to find an optimal internal path within each domain (or multiple paths if allowed).

Intra- and interdomain TE should be considered concurrently in implementation considering the network configuration and their consequent dependency on one another. Consequently, INPs must apply both intra- and interdomain TE in conjunction in order to meet the routing optimization objectives [2].

It should be noted that since all-IP access networks are at the edges of the Internet routing fabric, in this thesis, we focus on intra-domain TE accordingly.

2.2.2 IP vs. MPLS

Intra-domain TE can be categorized into the MPLS (Multiprotocol Label Switching)- and IP-based TE. Presently, MPLS is extensively deployed in access networks through which encapsulated IP packets are delivered over Labelled Switched Paths (LSPs). Traffic engineering was initially conceptualized in MPLS-oriented environments as a flow-based connection oriented protocol [37–40]. Explicit routing and arbitrary splitting of traffic are enabled through MPLS. However, scalability and robustness become an issue due to the complexity and overhead associated with building and maintaining LSPs to which flows are mapped and the extra information added to each packet [2]. The overall number of LSPs (with the assumption of full-mesh/connectivity or equivalent) within an AS is $O(N^2)$ where N is the number of ASBRs. This is indicative of a high LSPs provisioning overhead specially in case of large-scale networks. Moreover, ensuring back up LSPs is necessary in case of MPLS TE as traffic would not be automatically rerouted in case of node/link failure as opposed to IP-based TE.

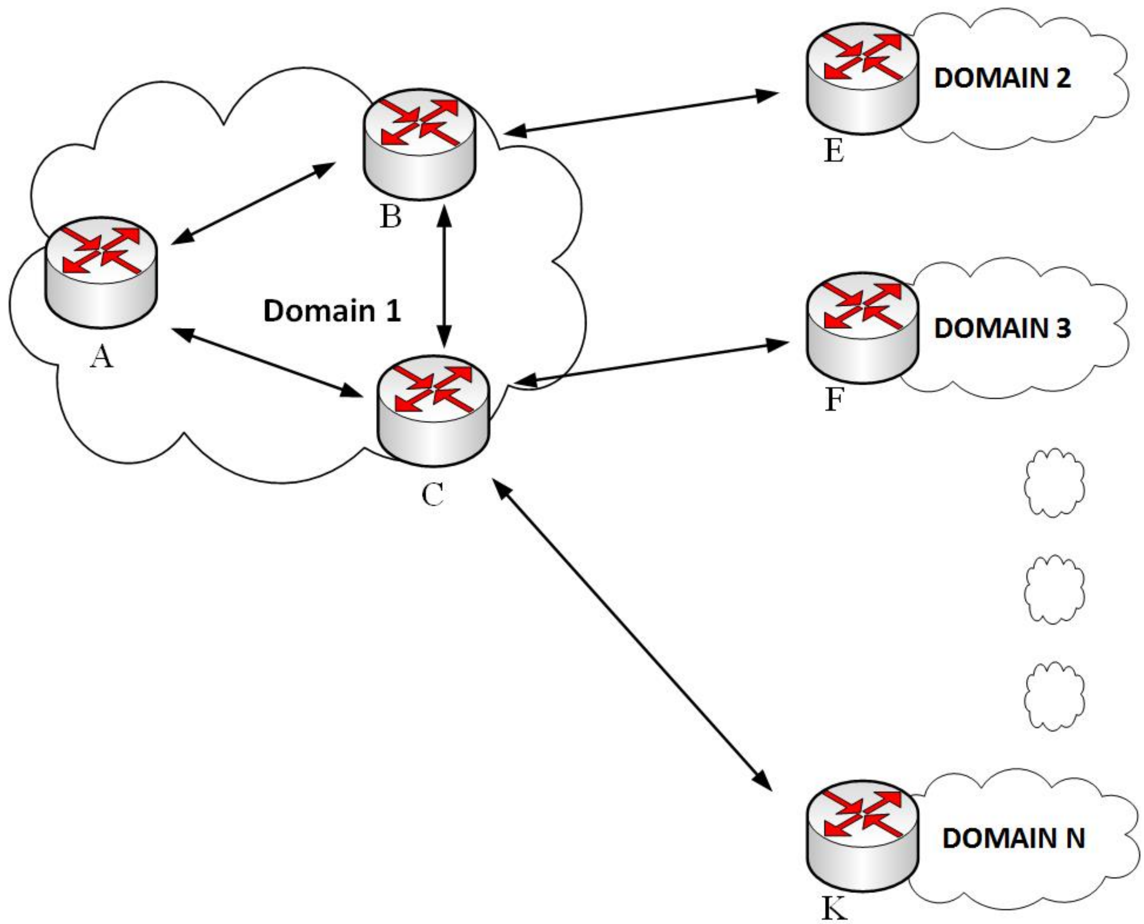


Figure 2.2: Scope of traffic engineering. IntradomainTE considers optimized routing for each node pair within the network; On the other hand, interdomain TE focuses on optimized ASBR selection

IP-based TE was initially proposed in [41–43]. The proposed IP-based TE is implemented through the manipulation of link weights in case of Interior Gateway Protocols (IGPs) such as Open Shortest Path First (OSPF) and Intermediate System - Intermediate System (IS-IS) protocol [44] which are commonly used intra-domain dynamic link-state IP IGPs. As opposed to MPLS TE, IP TE does not facilitate explicit routing and arbitrary splitting of traffic intrinsically as it is based on the shortest-path routing principle with relatively slow recalculation of paths. Nonetheless, as minimal overhead is associated with the path setups, IP-based TE benefits from better scalability and availability resilience compared to MPLS-based TE. Traffic can also be automatically rerouted via other shortest paths in case of node/link failure as an integrated solution of IP-based TE without the need for backup paths' provisioning. However, the auto-rerouting in case of IP-based TE might lead to traffic distribution imbalance causing congestion.

2.2.3 Offline TE versus Online TE

Traffic engineering can be classified in terms of planning for the available traffic demand or timescale of operations into offline TE and online TE.

The availability of a Traffic Matrix (TM) and the time-frame of traffic management are the main factors setting the offline and online TE approaches apart. A TM which was originally affiliated with intradomain TE, embodies the amount of traffic traversing between all pairs of ingress and egress in a given IP AS. In other words, a TM represents the total bandwidth demand of all individual traffic flows from an ingress node to an egress node. Subsequent to the TM evaluation for a given network topology, offline TE can be applied by an INP.

It is possible for the INPs to forecast the TM prior to routing optimization based on two main inputs: a Service Level Specification (SLS) and monitoring/measurement [45, 46]. As a SLS is agreed upon between the INP and customers, the INP can estimate the total bandwidth demand between each pair of ASBRs by cumulating every customer's traffic predictions. Moreover, traffic monitoring mechanisms can be applied at network borders for TM estimation purposes. Offline TE lacks traffic manipulation versatility given the traffic and network dynamics such as traffic burst, and failures. This lack of versatility renders the offline TE less efficient considering the actual traffic pattern's likely divergence from prediction. Meanwhile, it could prove to be difficult for Online TE to handle future incoming traffic based on the current network state. This is due to the unpredictability of the incoming traffic pattern caused by factors such as the lack of a global view on overall traffic conditions.

To overcome the issues associated with the offline and online TE mechanisms, it is recommended for a combination of both mechanisms to be applied as complementary TE components. To this end, offline TE can be applied as a behavioral guideline for the more adaptive and versatile online TE that can manage the dynamics which have not been predicted by the offline

TE. In this thesis, we apply an IP-based TE approach consisting of complementary offline TE and online TE components.

2.3 Existing Intra-domain IP Traffic Engineering Solutions

OSPF and IS-IS are commonly applied intra-domain hop-by-hop based protocols. Link-state hop-by-hop routing optimization mechanisms typically apply Dijkstra-based algorithms to discover a set of shortest paths based on the link weights [47–49]. It is argued in [50] that OSPF and IS-IS use link-state routing algorithms with hop-by-hop forwarding that sacrifice traffic engineering performance for ease of implementation and management. This has led to the adoption of other methods namely source routing and other non-link state approaches. Henceforth, we concentrate on OSPF as this research is concerned with the study, development and extension of OSPF-based IP networking.

OSPF is an IP-based dynamic link-state protocol through which the network has a complete view of the network state and topology. OSPF is dynamic, scalable, reliable and robust against link/node failures. However, OSPF's application could lead to the network's congestion underscoring the significance of traffic engineering adoption on the top for improved performance. Additionally, OSPF does not support arbitrary traffic splitting as opposed to MPLS. The authors in [51] propose a decentralized OSPF-based hop-by-hop solution aimed at achieving optimality enabled by distributing Link state Advertisements (LSAs) on an extremely frequent basis. However, since this approach uses a hop-by-hop solution, it burdens the routers in link weight computations.

Equal-Cost Multi-Path (ECMP) is an add-on option of OSPF based on which traffic is split roughly equally between multiple paths of equivalent cost through hop-by-hop forwarding. Fortz and Thorup [41, 43] showed that by optimising OSPF/IS-IS link weights aimed at load balancing, the network's performance could be improved as compared with the conventional link weight setting configuration using inverse proportional bandwidth capacity. As a result of this proposal, the traffic originally traversing one single path can be evenly split into multiple paths with equal OSPF/IS-IS weights based on ECMP. This study also proved that the optimal configuration of such link weights is NP-hard. Figure 2.3 provides an illustration of the proposed algorithm. In accordance, the traffic flow originating from X to t is split evenly between the available paths. In this case, as shifting traffic might render additional congestion to other links, preemptive local adjustments need to made accordingly.

ECMP cannot be configured in complex large-scale topologies as the quality of OSPF TE can become arbitrarily poor compared to optimal TE due to the computational intractability to derive optimal link weights for large-scale networks [14]. There are notable studies on improving the optimality of IP-based intra-domain TE mechanisms based on ECMP. The studies consider the possibility of achieving some immediate load balancing using path diversity by capitalizing on the flexible use of network topology.

The legacy ECMP has been specifically adopted by authors in [52] for improved ECMP based load balancing purposes. This is achieved by having a sub-set of available next hops selected for each destination prefix rather than dispensing the traffic equally between all the possible available next hops. An optimal ECMP-based TE method was proposed in [53] where virtual links are installed alongside the existing physical ones with the aim of tackling the stringent equal traffic distribution solely between paths of equal least-cost. However, the aforementioned ECMP-based schemes are still dependent on the link weight setting, making them slow, subject to performance degradation and deviation from optimal TE. To address the latter issues, authors in [54] proposed an ECMP-based protocol that applies Network Entropy Maximization (NEM) based on which traffic is to be split among all the available paths enabling the arbitrary splitting of traffic. Recent work [55] reapplies NEM to provide load balancing in IP networks using uneven ECMP-facilitated traffic splitting by introducing an alternate set of links weights while preserving the shortest path conditions in networks. However, these protocols are dependent on occurrences of equal cost paths in segments of networks where routers are involved in the calculations of entire paths [54] and path reconfigurations are in the order of minutes [55].

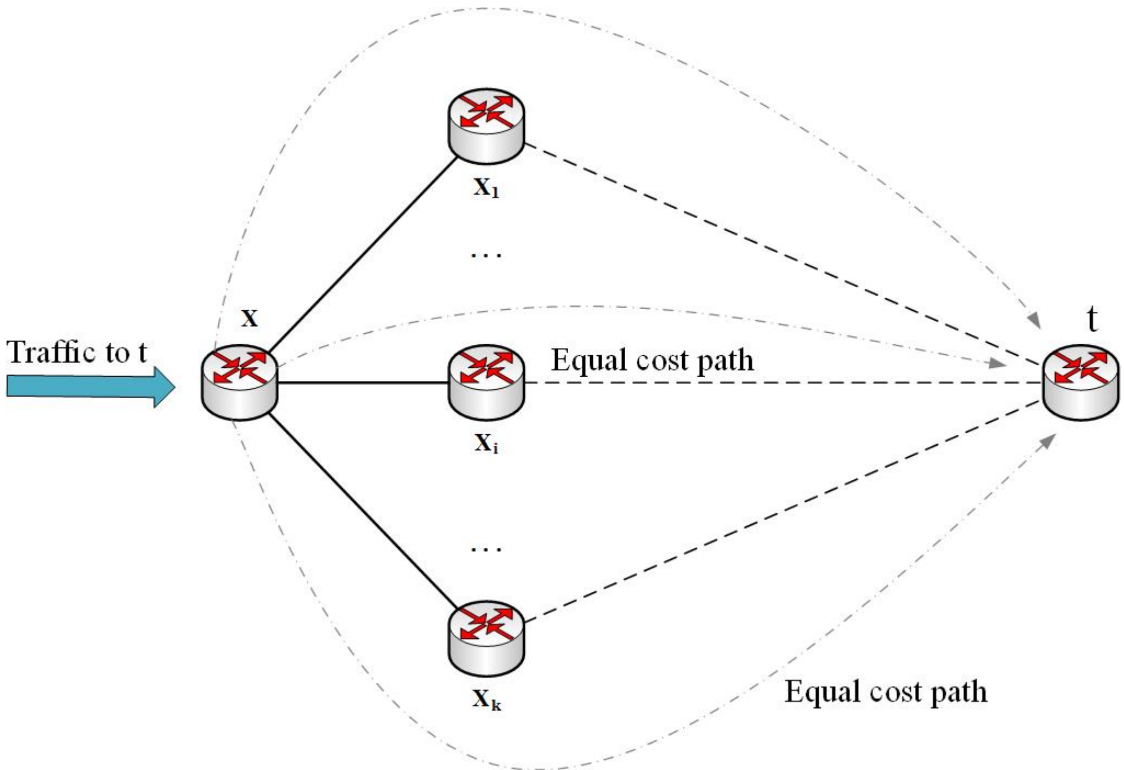


Figure 2.3: Fortz and Thorups link weight optimisation solution

2.4 The need for Path Diversity in Access Networks

As mentioned previously, the fast paced transformation of network services and applications calls for consistent adaptations in routing optimization mechanisms. The explosion of P2P approaches for gaming, telephony and television along with the rise of new applications namely IPTV and VoIP as well as new traffic types in the post-IP age further underscores the evolution in modern networks. Correspondingly, the rising traffic dynamism in line with the new application types, the abrupt traffic surges and variations, and the extensive deployments of application-layer overlays need to be catered for.

Given such transformations as indicated above, the network administrators have been increasingly considering multi-path routing with the aim of minimizing the extent of the link capacity upgrade. As discussed before, the legacy dynamic routing could be complex and unstable and lacks versatility to congestion. Multi-path routing is more efficient in utilizing the additional capacity and resources throughout the network in order to fulfill the incoming demands, possibly avoiding costly links' capacity over-provisioning, hence constituting a good strategy to be adopted in both current and future network architectures.

Multi-path routing approaches must take various traffic applications' behaviours into consideration while aiming to boost network performance by offering diversity. Most traffic applications namely bandwidth eager P2P (e.g. file-sharing and live-streaming) are adaptive to dynamic environments, allowing for an easier exploitation of network resources. Meanwhile, some applications namely conversational calls and short Web transfers can still not be split into several paths.

Path diversity and its potential benefits in access networks was investigated in [32]. [32] also undermined the need for next-generation access networks' evolution to more meshing in topologies, aligned with changes in traffic and heterogeneous access technologies, in order to exploit path diversity that can be achieved by multi-path routing. In the long term, the access networks should definitely implement native multi-path routing and flow control primitives in order to benefit from diversity. In fact, with the expected increase in the backhaul traffic [56], wired backhaul links' overload [30] could be alleviated by the diversity offered by multi-path routing. In this research, we consider path diversity as an underlying solution for improved network performance.

2.5 Multi-Plane Routing

Multi-Plane Routing (MPR) which was initially proposed in [17] aims to address the deficiencies associated with MPLS and OSPF/ECMP in increasingly relevant access networks' topologies. MPR is based on the Multi-Topology OSPF (MT-OSPF) principle [57] that enables multiple instances of OSPF in an intra-domain network. MT-OSPF was primarily proposed for fast re-routing in case of node/link failures [58, 59] but its principle was adapted for load balancing purposes in intra-domain networks [18]. MPR was built upon the use of MT-OSPF as applied in [18] for comprehensive network-wide load balancing by being specifically targeted for IP access network topologies. MPR is comprised of an offline TE method that serves to build logical Routing Planes (RPs) rendering a set of multiple shortest paths between all *Ingress* - *Egress* routers ahead of the traffic flow in the network that is then governed by an online TE approach. MPR's online TE approach was initially presented in [21] and [60] serving a practical purpose of an integrated solution of distributing IP sessions over RPs.

MPR's constructed logical RPs represent instances of OSPF such that path diversity is maximized. The RPs are built so that an optimum full utilization of links based on Full Path Diversity Index (FPDI) is achieved as outlined in [17]. Figure 2.4 illustrates how three sets of shortest paths can be combined to form three routing planes so as to maximise path diversity between a single ingress/egress pair (from node S to node D). It is notable that the set of shortest paths between every ingress-egress pair should not be necessarily disjoint.

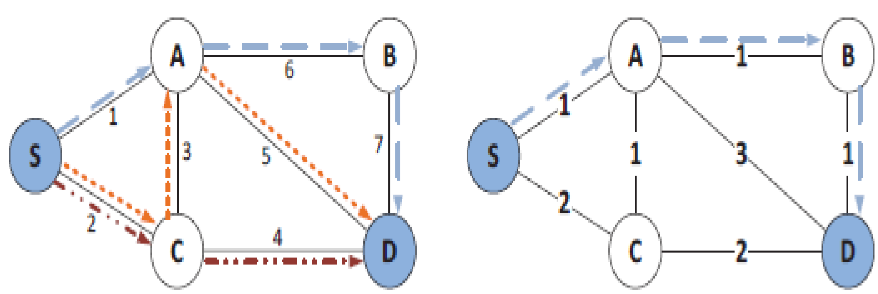


Figure 2.4: A simple example of 3 RPs. Numbers indicate link IDs (left) and link weights for one RP (right)

In case of legacy OSPF, as illustrated on the left side of Figure 2.5, one Routing Information Base (RIB, equivalent to a routing table) having been extracted from the topology database pertaining to the control plane followed by one Forwarding Information Base (FIB, or forwarding table) pertaining to the data plane, is used. In case of MPR (i.e. bold lines in Figure 2.5), one RIB/FIB is associated with every routing plane. Accordingly, flows are mapped to specific planes selected by concerning routers and then routed based on the corresponding RIB. With regards to packet association with planes, there are some proposed solutions for mapping traffic to RPs [58, 61].

MPR achieves explicit routing and arbitrary splitting of traffic (as achieved under MPLS TE approach) by applying an IP-based TE approach. Therefore, the complexity and overhead associated with the MPLS TE approach can be avoided. Recent proposals [62] similarly classify and apply practicality in bridging the characteristics of explicit routing (e.g. MPLS) and destination-based routing (e.g. IP-based routing such as OSPF) toward the goals of path diversity offered by multi-path routing. Relevance of path diversity in access networks' evolution has inspired further studies on MPR in [19] and [20] that provide the foundations for this thesis. [19] contains a theoretical study of the offline's quality of RPs when extended with internal traffic routing paths subject to hop-constrained optimization. Early practical results with the added internal traffic distributions for one topology are presented in [20] with the readjusted online TE approach as compared with [21] and [60].

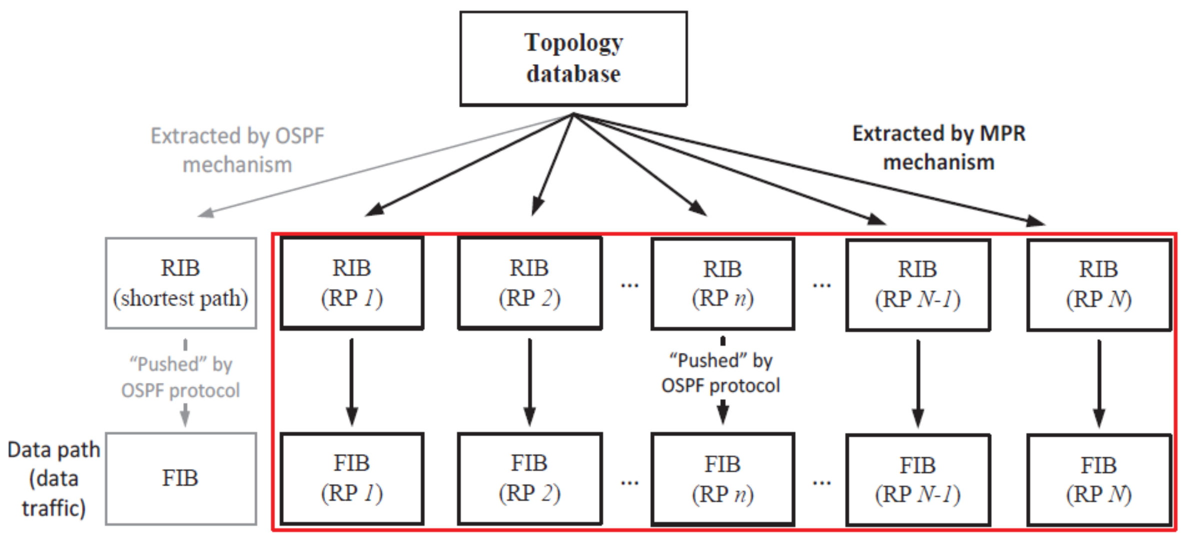


Figure 2.5: Data flow in case of legacy OSPF and MPR

2.6 Quality of Service

For a long time, the Internet has treated all traffic packets (e.g., data, voice, video) similarly without QoS provisioning. Such a best effort data delivery approach cannot be maintained much longer given the huge surge of traffic volume throughout the Internet and the associated increasingly variant traffic types. Therefore, the migration to a service differentiation oriented model seems inevitable. Correspondingly, the Internet and mobile applications are increasingly demanding stringent QoS requirements with a Service Level Agreement (SLA). The emerging access networks (cellular- and Internet-based) should also support more complex mechanisms for traffic differentiation than those of legacy approaches in order to address the increasingly diverse and stringent end-to-end QoS requirements [24]. A SLA ensures guaranteed traffic perquisites namely low latency, jitter and packectloss for real-time services such as VoIP and video on demand along with high throughput for bandwidth hungry applications. It should be noted that problems comprising two or more additive QoS constraints have been shown to be NP-hard [63]. Providing QoS guarantees in packet switched access networks gives rise to several challenging issues as there are multiple aspects of QoS to be considered. For example, to support video communication high throughput is required and therefore, high bandwidth guarantees will have to be made. Audio communication, in contrast, does not usually require high bandwidth. End-to-end delay and delay variations are other factors that must be taken into consideration for time-critical traffic such as VoIP. Meanwhile, over the past few years, many scientists have envisioned an Internet generation that will not only provide voice and data communications but can also support haptics communication. Tactile Internet has very strict QoS metrics namely the need for an extremely high reliability indicating a very low packet loss along with low latency and jitter.

In addition, increasingly variant multi-gigabit backhaul traffic needs to be catered for in ultra dense cell networks with guaranteed QoS in order to meet the users' expectations [56]. Flow-based QoS routing with the aim of identifying routes that meet the QoS constraints while efficiently using network resources was studied in detail in [64]. Moreover, QoS provisioning in next generation access networks will potentially necessitate identification of packet contents followed by dynamic control of the packet transport infrastructure to mark and prioritize packets and in some cases coupled with dynamically updated packet routing policies [65].

2.6.1 QoS Protocols

There exist two fundamental QoS architectures: Differentiated Services (DiffServ) [66] and Integrated Services (IntServ) [67].

The IntServ architecture was introduced to address the variable queueing delays and congestion losses in case of surging real-time applications such as remote video, multimedia conferencing, visualization, and virtual reality [68]. In the IntServ model, a packet's traffic class is identified through a signaling protocol as a guideline to the routers for QoS treatment. This model facilitates end-to-end QoS by provisioning per-flow state QoS requirements (i.e. providing QoS to specific flows). IntServ establishes and maintains QoS by applying Resource Reservation Protocol (RSVP) to explicitly broadcast the QoS requirements in end-to-end paths throughout the network. Once the required bandwidth is guaranteed in a given path, the transmission would commence. IntServ supports two types of service: controlled-load service and guaranteed service. Controlled-load service provides for a better than best effort and low latency service under light to moderate network loads. Meanwhile, guaranteed service enforces strict bounds on end-to-end delay and guaranteed bandwidth for traffic which conforms to the reserved specifications [69].

The DiffServ model was proposed to facilitate service differentiation eliminating the need for per-flow state and signalling in every router. In this case, the packet's class can be marked directly in the IP header (IPv4 ToS octet or the IPv6 traffic class octet) in order to facilitate a specific forwarding treatment, or per-hop behavior, at each network's router. The model achieves better scalability and versatility by being comprised of two main elements: forwarding path and management plane [70].

It is notable that these two QoS mechanisms are not mutually exclusive and can be implemented complementarily.

2.6.2 Tactile Internet

The progressive Internet deployments have facilitated a better performance in terms of network characteristics (i.e. delay, packet loss, jitter etc.). Such improvements have given rise to the opportunities to deploy new applications and technologies that help us improve our daily lives. Over the last years, many scientists and organizations have been considering an Internet generation that will enable a new dimension in our communications, i.e. the sense of touch. This new dimension is now widely known as the so-called Tactile Internet, a term that was first introduced by G. P. Fettweis in 2014 [71,72]. Tactile Internet embodies an ultra-responsive and ultra-reliable network connectivity that will enable the delivery of physical haptics experiences remotely, adding a new dimension to human-machine interaction [73]. The technical specifications of Tactile Internet have been proposed by the International Telecommunication Union (ITU) [74] to revolutionize 'Machine to Machine' (M2M) and 'Human-to-Machine' (H2M) communications [16]. Accordingly, the main constraints of this new Internet dimension are extremely strict. Namely, ultra-low latency and a round trip time lower than 1ms. In the case where latency would exceed the threshold of 1ms, the Tactile application's user would not be able to control real and virtual objects without facing cyber-sickness. Another key challenge is to facilitate an extremely high reliability. Correspondingly, a packet loss even below 10^{-7} might be necessary in some cases. Finally, the variability over time of the packet's latency across a network (i.e. jitter) should not be greater than 20 μs.

Vendors have envisioned and proposed some potential benefits of this new Internet generation [71, 74, 75]. Tactile Internet will facilitate the development of new applications and opportunities that will have a significantly positive impact on society and business. The proposed applications can be applied in many different sectors and fields ranging across various industries. One example is the facilitation of dynamic activation and deactivation of local power generation and consumption in smart grids. Furthermore, as an effective tool in general remote control in robotics, this revolutionary concept can improve the health care sector by enabling surgery trainings. Tactile Internet will also gives rise to the possibility of improving the livelihood of people who reside in urban and remote areas. A market analysis has predicted that the potential market value for this new Internet generation could exceed 20 trillion dollars worldwide, which would account to approximately 20 percent of worldwide GDP [76].

Currently, the Internet supports voice and data communications in addition to multimedia services such as audio and video. Nonetheless, the tactile Internet must enable haptics communication [77] as a major application and provide the medium for transporting haptics information. Such information can be classified based on two different types of feedback [73]: kinaesthetic feedback (i.e. information that comes from proprioceptors within the body namely about position, force etc.) and Tactile feedback (i.e feedback that is related to the touch sense i.e. texture). Tactile Internet communication is expected to be feasible in scoped and/or reasonable communication distances. This is due to the requirements being hard to control over the ranges of Internet networks that can be traversed by the packets with different traffic flow requirements. In order to facilitate adequate QoS as well security for Tactile applications, the authors in [78] have suggested the thinning of the core network which can be achieved by its functional decomposition and the transition of some of core functionalities to the access network. This will in turn minimize the number of nodes in the data path leading to the reduction of end-to-end latency.

As illustrated in Figure 2.6 [73], the end-to-end architecture for Tactile Internet providing the medium for haptics transport can be divided into three distinct domains: the master domain, the network domain , and the slave domain [73]. The network domain facilitates the medium for bilateral communication between the master domain and the slave domain, kinesthetically connecting humans to the remote environment. In the ideal case, the operator is entirely immersed in the remote environment. It should be noted that Tactile Internet within scoped network domains is of concern in this thesis.

There have been studies conducted on Tactile Internet that are not coherently developed and

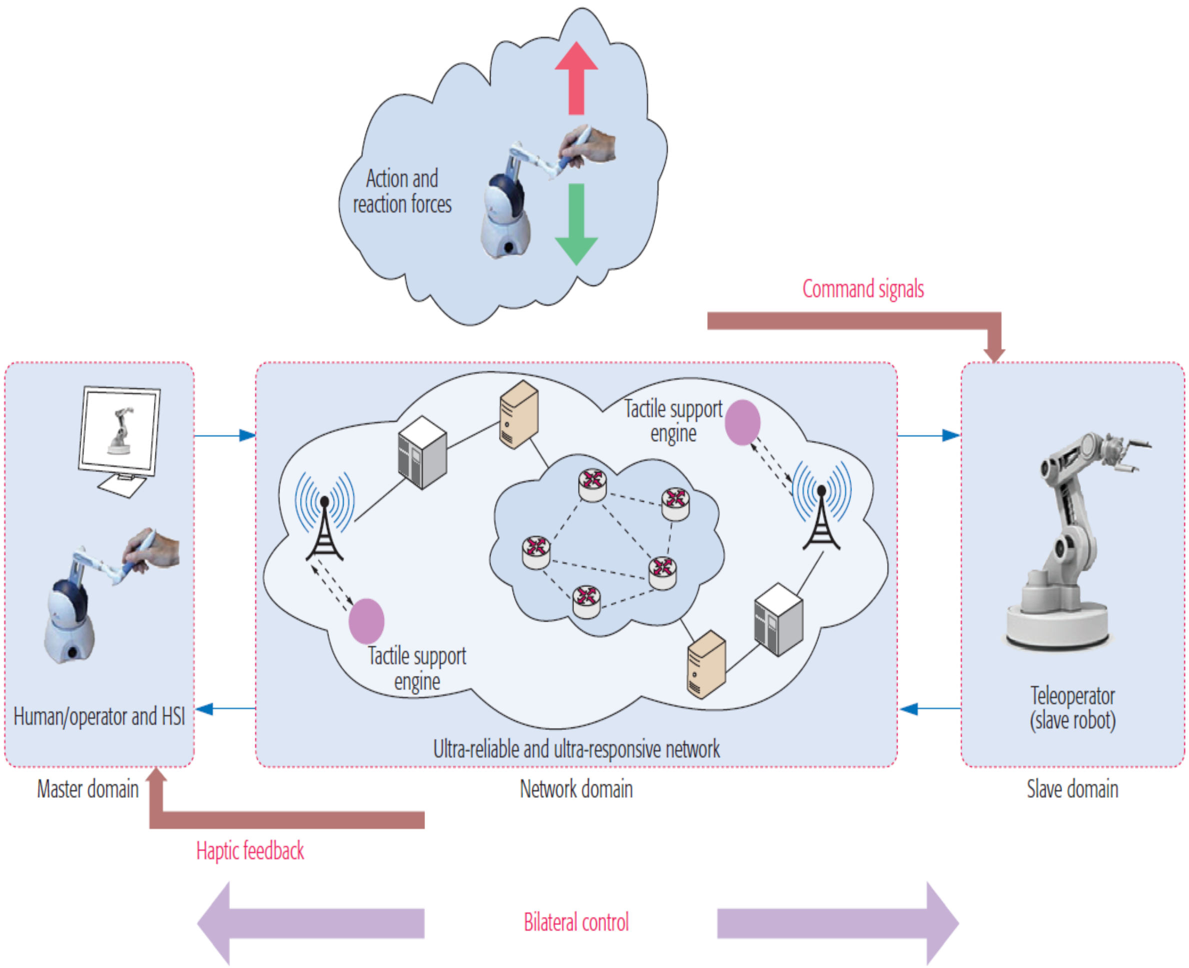


Figure 2.6: Functional architecture of the Tactile Internet providing the medium for haptic transport

do not focus on a single Internet aspect, rather, a collection of proposals and thinking towards meeting some general requirements for the Tactile Internet. Different techniques have been proposed for predicting motion and force information in haptic media even for non-linear haptic movements and force information [79]. Some studies have used the prediction techniques so as to reduce the network effects such as delay. Correspondingly, by predicting motion, force and compressing haptic data, the stringent network effects such as delay, jitter and packet loss can be relaxed and alleviated [80]. There have been efforts in ensuring Tactile secure deterministic for tactile packets delivery in core networks via Software Defined Networks (SDN) [81].

The authors in [71] outline the importance of the physical packet length by stating that it should not exceed 33μs packet duration so as to achieve a round-trip latency lower than 1ms.

Furthermore, it is mentioned that the modulation technique that is used by LTE is not a feasible solution because of an Orthogonal Frequency-Division Multiplexing (OFDM) symbol alone being of the order of 70 μs. Consequently, a new cellular system has to be designed in order to support the Tactile Internet. Also, a candidate solution for Tactile packets over wireless networks would be the TCP/IP packets bypassing the MAC layer and being forwarded directly to the physical layer. Emphasis is placed on the fact that current systems have little provisioning for defining the minimum latency of protocol handing. Another interesting article on the Tactile Internet [82] shows that latency and packet re-transmission can be reduced significantly by combining network coding and SDN. However, for simplicity, this study is based on a simple multi-hop network topology and does not explore the case of large and realistic topologies of Internet networks with the possibility of path diversity and exploring the multi-path routing for expediting routing characteristics for certain types of traffic.

In Chapter 6, we propose a novel routing scheme that accommodates for Tactile-oriented Internet traffic in consideration of the strict QoS requirements.

2.7 Summary

In this chapter, the preliminaries and the corresponding related work were presented. The extension of IP infrastructure presents new opportunities for network administrators. Meanwhile, the Internet has significantly transformed with the huge surge of traffic volume and the rise of new types of applications. The introduction of the Tactile Internet exemplifies the rising new traffic types that are flooding the Internet. Given this transformation, it has become essential for INPs to apply traffic engineering. Moreover, the architectural evolution of all-IP access networks aligned with the developing 5G and networking concepts call for consistent adaptations in routing optimization mechanisms. Path diversity was discussed as a crucial underlying integrated traffic engineering factor in access networks. Multi-Plane Routing (MPR) that integrates path diversity in its approach, aims to provide a novel IP intra-domain TE solution for future all-IP access networks.

In the upcoming chapters (Chapters 3-6), MPR will be further investigated and extended to reflect practical aspects and applications such as the architectural evolution of IP access networks and the introduction of Tactile applications along with the consideration of a comprehensive traffic distribution breakdown. In addition, extensive comparisons against rival strategies namely MPLS and OSPF will be provided.

3

A New Approach to Offline Routing Plane Construction in Future Multi-Plane Routing based IP Access Networks

3.1 Introduction

There has been a rapid rise in IP traffic throughout the Internet which takes advantage of the already established widespread IP infrastructure. Different suggestions are being explored about the facilitation of next-generation access networks via IP mechanisms, with a growing trend towards a flat IP structure and novel topological set-ups in the backhaul. Aligned with this evolution, there are increasing number of user applications flooding the Internet that calls for a consistent routing strategy to minimize loss in data transmission. In this chapter, MPR which incorporates various aspects of an all-IP infrastructure will be studied under the new access network structure. MPR is based on the MT-OSPF principle and divides the physical network topology into several logical Routing Planes (RPs). MPR is designed to improve the network's performance through the application of an offline TE method in order to build RPs ahead of the traffic flow in the network which follows an online TE approach [17,60]. MPR is envisioned to be configured using the IP-header integrated ToS/DiffServ's unused bits (i.e. 3 precedences). A reference scenario topology was applied showing how MPR outperforms OSPF in terms of different network metrics [17]. The case where there exist dedicated paths for every *Gateway* (GW)-*Aggregation Router* (AR) pair was previously studied. Under this scenario, the traffic destined for outside of the network towards the big Internet and the internal traffic between the ARs would pass through the gateway. This structure is restricted to 3G environment's architectural functionality where the entire traffic travels through the core. We are targeting to expand our model to converge the Internet routing and future cellular systems' requirements by modifying the RP structure, allowing for direct communication between the ARs. To this end, the offline Traffic Engineering (TE) strategy for MPR has been optimized using a heuristic hop-constraint solution to suit the "flattened" network, realized through the incorporation of direct communication between aggregation routers. With our approach, despite having more $Ingress-Egress$ pairs for traffic in the access network, the number of RPs has been kept to the desirable level whilst the reliability indicator and the path diversity index ratio have increased up to 47% and 33%, respectively. Our proposed MPR-based offline approach has also shown improvements compared with the MPLS offline approach.

3.2 Investigated Network Model

3.2.1 Concept

MPR divides the network into multiple logical planes. This allows the routers in one OSPF area to maintain several independent logical planes. Each RP is an instance of OSPF associated with a dedicated link weight configuration and it can overlap with another or share any subset of the underlying network. Figure 3.1 illustrates the RP distribution in our reference network. In our study, each router will have different Routing Information Bases (RIBs) and Forwarding Information Bases (FIBs) through which routes between ARs and the gateway are defined in every plane. Each RIB/FIB represents one RP.

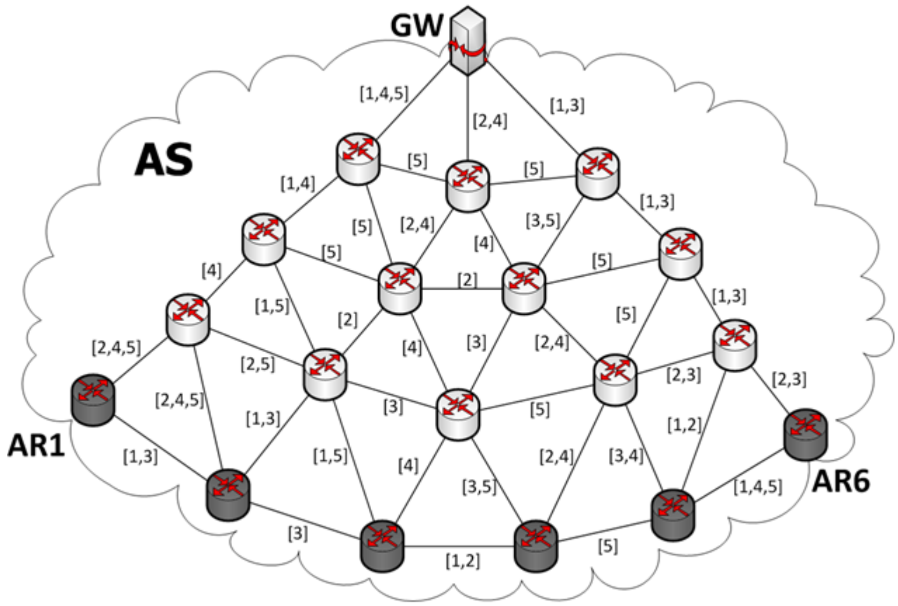


Figure 3.1: Autonomous system comprised of 32 nodes and 67 links. Average node degree: 4.19. Total capacity (Gb): 18.40

3.2.2 Simulation Setup

The network in Figure 3.1 represents an Autonomous System (AS) which can be a campus or metropolitan access network with a single gateway towards the big Internet. This reference fat-tree model is based on [23]. Nodes are considered to be interconnected by wired Ethernet links. It has been argued that wired backhaul technologies benefit from high reliability, high data rate, and high availability [83]. The network is comprised of 6 base stations acting as Aggregation Routers. Link capacities are set up depending on the level (determined based on proximity from the GW, Figure 4.1) they belong to as demonstrated in the reference network (following a uniform distribution). [360, 400], [200, 240], [140, 180] and [60, 100] Mbps (values used for normalization) are used for four different levels respectively in the first studied network (19 nodes). [360, 400] , [160, 200], [110, 150] (for Level 3 and 4), and finally [50, 90] Mbps are used for five different levels respectively in the second studied network (32 nodes) with 14 base stations. It should be noted that the network portrayed is the base topology to which different meshing degrees (node degrees) are applied in order to create several sub-

Topo	Nodes	ARs	Links	Avg. Node degree	Total capacity (Gb)
T1M1	19	6	18	1.9	7.84
T1M2	19	6	32	3.36	11.94
T1M3	19	6	36	3.79	12.98
T1M4	19	6	39	4.1	14.06
T1M5	19	6	41	4.32	15.34
T2M1	32	14	31	1.94	9.84
T2M2	32	14	53	3.31	15.28
T2M3	32	14	59	3.7	16.48
T2M4	32	14	61	3.82	16.88
T2M5	32	14	65	4.06	18.00
T2M6	32	14	67	4.19	18.40

Table 3.1: Configuration of the meshed topologies

topologies. The RPs are built considering that traffic can exist internally between the ARs and towards the Internet through the gateway. Table 3.1 presents the specifications of the eleven investigated topologies to provide diversified network scenarios for demonstrating the concepts of MPR. x indicates the topology number and y denotes the meshing configuration in every topology $TxMy$. $T1M1$ and $T2M1$, which are sub-topologies for the network 1 and network 2 respectively, represent strict trees. $T2My$ topologies include added ARs spread out in the transit space which set it apart from the previously studied scenario with ARs strictly located at the edge, i.e. $T1My$ topologies.

3.2.3 Outline and Contributions

We extend the research conducted in [17] and [60] by building direct communication paths between the ARs in our reference topologies (as normally envisaged in OSPF implementations). This is achieved through the modification of the RP structure and based on the newly proposed RP construction methods. To this end, the offline algorithm has been extended and enhanced. In addition to topologies with ARs strictly positioned at the edge, new topologies are added to our study with ARs spread out in the transit space. In this chapter, we focus on the offline TE aspect (network planning phase) of MPR which has the physical topology with associated link capacities as the input. Under the new scenario, the topology independent RP construction is optimized through the introduction of new properties to the RP construction algorithm. Our design concept is equally reflected in the trends towards a flat IP structure in cellular networks [9, 84]. Hence, base stations are directly interconnected by IP and the forwarding domain barriers in these networks (i.e. radio access and core networks) are being abolished making the new backhaul connection space open to diversification of paths via meshed hierarchical topological set-ups. In fact, with the expected increase in the backhaul traffic, wired backhaul links' overload could be alleviated by the diversity offered by MPR. Since we add AR-AR routes under the new scenario, each plane would end up with a larger number of paths than in the initially investigated scenario, hence the overall hop-count and utilization of the topology in each plane become important metrics. In earlier studies for MT-OSPF [58], it was concluded that overall near-optimal network performance in terms of cost and link utilization can be achieved with up to 3-5 RPs as also substantiated in [17] for MPR and other practical algorithms for creating routing planes [85, 86] in terms of achieving near-optimal TE performance. Lower number of RPs would also ensure minimum implementation and routing table maintenance overhead. In order to obtain the desired number of planes aimed at the improvement in the QoS performance as concluded in [87], a hop-constraint was introduced. It was shown that despite the hop-constraint's application leading to higher path costs, it improved the QoS and service delivery for the various tested network designs. Hop-constraint can be associated with lower delays. The traversal of many links during transmission leads to higher overall delays [88]. Hop-constraint is also aligned with reliability defined as the probability of the session for every $Ingress - Egress$ pair not being interrupted by any external factors such as link failure [89]. Lower reliability can have a negative impact on service delivery and QoS performance [90]. RP construction considering the aforementioned metrics is investigated through the introduction of the Quality of Plane-set (QoP) which provides an analytical overview of the constructed RPs' configuration efficiency. The superiority of our MPR-based approach over the MPLS offline approach will also be demonstrated.

To summaries, this chapter contains four main contributions: First, the extent of building paths in each logical topology by adding direct paths between ARs in our reference topologies is investigated using three novel heuristic RP construction methods that are proposed. Second, hop-count will be introduced as a constraint in each plane which is used as an investigation parameter for finding the optimal configuration based on the number of RPs in physical topologies. Third, a method for assessing the quality of logical topologies is proposed. Finally, it will be shown that the proposed MPR-based approach outperforms the offline MPLS LSP construction method.

3.3 Graph Theoretical Representation

Let the topology of a given communication access network be represented by a connected directed graph $G = (\mathcal{V}, \mathcal{E})$, with a set $\mathcal{E}$=$\{e : e = 1,...,E\}$ of edges with finite capacities C_e, and a set $\mathcal{V}$=$\{v : v = 1,...,V\}$ of vertices. Let $\mathcal{K}$=$\{k : k = 1,...,K\}$ symbolize the number of ARs in the network whereas the GW is symbolized as $K+1$. Let the set of Routing Planes (RPs) be represented as $\mathcal{N}$=$\{n : n = 1,...,N\}$. Every $e \in \mathcal{E}$ is assigned with N distinct link weights denoted by $w(n,e);\forall n \in \mathcal{N}$. The network supports a set of overall traffic flows for every *Ingress* - *Egress* pair that are referred to as demands and is denoted by $\mathcal{D}$=$\{d : d = 1,...,D\}$. In addition to the GW as a possible source of traffic, let $AR_{\mathcal{A}}$ ($\subseteq AR_k$) be the source AR ($\mathcal{A}$=$\{a : a = 1,...,A\}$). The *Egress* nodes are:

$$Egress : \begin{cases} \{AR_k\}_{k=1}^{K}, \text{ when } GW \text{ is } Ingress \\ \\ \{AR_k\}_{k=1,k\neq a}^{K} \cup GW, \text{ when } AR_a \text{ is } Ingress \end{cases} \tag{3.1}$$

AR_{fi} represents the first destination AR while AR_{la} represents the last destination AR in the network in one path set (ρ_n^k) pertaining to a particular source in the iteration. Subsequently, the source AR (AR_a) changes for the next iteration until all the ARs and the GW are covered (i.e. an instance of OSPF, one RP). The connections are duplex therefore, all the destinations can be sources as reflected in the overlapping RPs built for all the ARs and GW. Every RP is comprised of $\rho_n^{\mathcal{K}} = \{\rho_n^k : k = 1, ..., K+1\}$ set of shortest paths. $\rho_n^{\mathcal{K}}$ incorporates the demand-set $\mathcal{D}$ for $\{P_n^d\}_{d=1}^D$ in RP n for all the ARs and GW. Therefore, there are $\{P_n^d\}_{d=1}^D \subset \rho_n^{\mathcal{K}}$ acyclic shortest paths for RP n according to the link weight configuration W_n for that RP. The position of every link in path P_n^d is represented by a set of $\mathcal{H}_n^d = \{h : h = 1, ..., H_n^d\}$ hops from the *Ingress*. An $N \times E$ matrix R^d represents the link usage. $R^d_{eP_n^d} = 1$ if path P_n of pair d uses link e and $R^d_{eP_n^d} = 0$ otherwise. Matrix R^d for demand d is:

$$R^d = \begin{bmatrix} R^d_{1P_1^d} & R^d_{2P_1^d} & \cdots & R^d_{EP_1^d} \\ R^d_{1P_2^d} & R^d_{2P_2^d} & \cdots & R^d_{EP_2^d} \\ \vdots & & & \\ R^d_{1P_N^d} & R^d_{2P_N^d} & \cdots & R^d_{EP_N^d} \end{bmatrix} \tag{3.2}$$

The Path Diversity Index (PDI) as originally presented in [17] represents the number of RPs that include an e in their shortest path for demand d:

$$PDI_e^d = \sum_{n \in \mathcal{N}} R^d_{eP_n^d} \quad \forall e \in \mathcal{E} \;\; and \;\; \forall d \in \mathcal{D} \tag{3.3}$$

The ultimate objective is to minimize the chance that for a given demand all RPs share a single link; secondly to maximize the chance that any link is used in at least one RP. Full Path Diversity Index (FPDI) is introduced in [17] which designates whether a critical link e is included in shortest path for pair d in all RPs. FPDI is equal to 1 if $PDI_e^d = \mid N-1 \mid$ and 0 otherwise. The link weight assignment is described as follows: to calculate $\mid N \mid$ set of positive link weights $W_n = w(n,e) : 1 \preceq w(n,e) \preceq L$, with $\forall n \in \mathcal{N}, \forall e \in \mathcal{E}$ and $L(= 2^{16} - 1)$ as the highest value that OSPF can handle in order to maximize:

$$\sum_{d \in \mathcal{D}} \sum_{e \in \mathcal{E}} FPDI_e^d \tag{3.4}$$

The set of path matrices $(\rho_n^1, \rho_n^2, ..., \rho_n^K, \rho_n^{K+1})$ for all the ARs and GW represent one RP.

$$\rho_n^k = \begin{Bmatrix} AR_S & . & . & . & GW & : P_n^{d_k=1} \\ AR_S & . & . & . & AR_{fi} \neq AR_S & : P_n^{d_k=2} \\ \vdots & & & & & \\ AR_S & . & . & . & AR_{la} \neq AR_S & : P_n^{d_k=K} \end{Bmatrix} \tag{3.5}$$

The AR-GW pair is reserved in every RP for the case that the network ID of the desired address is located outside of the network and vice versa. $d = 1$ represents the AR1-GW pair in path-set ρ_n^1 and the demand increments up to D corresponding to the final pair in path-set ρ_n^{K+1}. $\bar{\varphi}_s$ is represented as the average length of the shortest path in terms of hop-count from any source u to all the destinations v across the available planes under a given topology. $\varphi_n^k(u, v)$ is the length of the shortest path from node $u \in Ingress$ to $v \in Egress$ in every path-set ρ_n^k.

$$\bar{\varphi}_s = \frac{1}{N} \left(\sum_{n=1}^{N} \sum_{k=1}^{K+1} \left(\frac{1}{K} \sum_{(u,v)\varepsilon V, v \neq u} \varphi_n^k(u, v) \right) \right) \tag{3.6}$$

3.4 RP Construction

The pseudo-code of the RP construction algorithm is presented as **Algorithm 2**. Initially, Cisco's InvCap is applied in assigning weights to the links. i.e. for each link $e \in E$, $w(1, e) = 1/C_e$. After building the first RP, three heuristic methods are used for computing the link weights 1) Iterative Plane Construction. 2) Link Degree of Involvement 3) Maximum link degree involvement per demand. The link weight configuration for these methods is obtained as follows:

$$\begin{aligned} w(n, e) = \frac{1}{C_e} + \frac{1}{n} \sum_{\rho=1}^{n-1} w(\rho, e) \\ + X \cdot \lambda_e(n) \end{aligned} \tag{3.7}$$

with $\forall e \in \mathcal{E}, \forall n \in [1, N-1]$ and with the following:

$$\alpha_e(n) = \begin{cases} 1, \text{ if link } e \text{ is in a path in RP } n-1 \text{ ;} \\ \\ 0, \text{otherwise} \end{cases} \tag{3.8}$$

$$\beta_e(n) = \sum_{n=1}^{N-1} \alpha_e(n) \tag{3.9}$$

$$\gamma_e(n) = \max_{d \in \mathcal{D}} \left(\sum_{n=1}^{N-1} \alpha_e^d(n) \right) \tag{3.10}$$

$\alpha_e(n), \beta_e(n), \gamma_e(n)$ represent method 1, method 2 and method 3 respectively as denoted by $\lambda_e(n)$ in equation 3.7. X is a multiplicative parameter that is used for the granularity of the methods. The higher the value of X, the more RPs will be tested. X ranges from 1 to X_{max} incremented by 1 with $X_{max} = \{2; 4; 8; 16; 32; 64\}$. Method 1 only considers the involvement of a link in RP in $N-1$. Method 2 considers the involvement of a link e in all RP $n \in [1, N-1]$. Method 3 is in fact a subset of method 2 where the cost of the most used link e in RP n is penalized. Subsequently, correlation between the three contending planes resulting from the aforementioned methods is calculated against the initial RP. The mean correlation is obtained for the resulting RPs from the $(1 : X_{max})$ loop and the plane with the lowest correlation is picked, having run the Djisktra's algorithm for the different weight-sets. There is a set of rules (i.e. prime objectives) which should be met in the RP construction algorithm: 1) Each link must not be utilized in at least one plane. This is to ensure that PDI_e^d does not reach beyond its maximum $(\mid N-1 \mid)$ per link. 2) There exists a route for every demand. Routers in between can be either sources or sinks. 3) The cost between every source-destination pair is minimum for each plane subject to the assigned link weights. 4) Each link is used in at least one plane in order to ensure path diversity.

Algorithm 1 Offline Algorithm for Building RPs

1: **procedure** RPs-CONSTRUCTION
2: Build the first InvCap link weights-based RP
3: **if** prime objectives (1-4) are met: jump to step 9
else: go to step 4
end if
4: **for** $X = 1 : X_{max}$
Derive sets of weights for candidate RPs using the methods in equations (3.8), (3.9) & (3.10) respectively
end for
5: Run Dijkstra to create candidate RPs based on the sets
6: **for** $n = 1 : X_{max}$
if the candidate RP n meets objectives 2 & 3 (hence a valid RP)
Record the candidate RP and its hop-length value H_n
end if
end for
7: Find the best RP n originating from step 6 (three methods) through correlation with the lowest possible hop-length while ensuring constraints' criteria are met (i.e. equation(3.13))
8: Go back to step 3 (i.e. the verification process)
9: RPs are obtained consisting of AR-AR and AR-GW pairs corresponding to Case I or II
10: **end procedure**

3.5 Plane-set Selection Criteria

3.5.1 Hop-Constraint Optimization

When applying MPR's off-line algorithm to build RPs connecting the AR-AR and AR-GW pairs, the resultant paths would render long routes between the ARs in terms of hop-count. Some of these routes would pass through the gateway or through nodes located very high in the distribution layer. This would not be desirable in our study to apply the MPR's technique under the new scenario where access points communicate directly. The long routes between ARs contribute to a higher number of RPs constructed per topology as there will exist more redundant paths available per plane. That's why hop-constraint is used to select an optimal set of RPs. Hop-constraint optimization was originally introduced in [91]. Here, more constraints have been added and certain representations have been reformulated in order to adjust the optimization problem to this work. The weight of link e between any two nodes (u, v) for demand d in plane n is denoted by $w_{uv}(n,e)$. The decision variables are defined as followed:

$R^d_{(uv)P^d_n}$ is defined as the binary directed variable which indicates whether $arc(u,v)$ is in the minimal tree and $Z^d_{(uv)P^d_n}$ is the directed binary flow variable that indicates whether $arc(u,v)$ is included in the only path from the *Ingress* t to the *Egress* node $s \in Egress$ at position h in RP n.

$$Z^d_{(uv)P^d_n} = \begin{cases} 1, \text{ if arc}(u,v) \text{ is in the path from root node t} \\ \quad \text{to node } s, s \neq u \\ 0, otherwise \end{cases} \tag{3.11}$$

We are minimizing the number of hops across a set of RPs obtained under a given topology. ($\forall e \in \mathcal{E}$ & $\forall d \in \mathcal{D}$)

$$\min \sum_{n=1}^{N} \sum_{(u,v)\varepsilon V} w_{uv}(n,e).R^d_{(uv)P^d_n} \tag{3.12}$$

s.t.

$$\begin{cases} 2 < N < 6 \qquad \forall Topolgies \neq \text{T1M1,T2M1} \qquad (1) \\ \sum_{(u)\varepsilon V} R^d_{(uv)P^d_n} = 1 \qquad \forall v\varepsilon V \neq AR_S/GW \qquad (2) \\ \sum_{(i)\varepsilon V} Z^d_{(uvs)P^d_n} - \sum_{(i)\varepsilon V \neq t} Z^d_{(uvs)P^d_n} = 0, \\ \qquad \forall s, v\varepsilon V \neq AR_S/GW, v \neq s \qquad (3) \\ \sum_{(u)\varepsilon V} Z^d_{(uvv)P^d_n} = 1 \qquad \forall v\varepsilon V \neq AR_S/GW \qquad (4) \\ \sum_{n=1}^{N} \sum_{(u,v)\varepsilon E} Z^d_{(uvs)P^d_n} \leq H.D.N \quad \forall s\varepsilon V \neq AR_S/GW \qquad (5) \\ Z^d_{(uvs)P^d_n} \leq R^d_{(uv)P^d_n} \qquad \forall (u,v)\varepsilon E, s\varepsilon V \neq AR_S/GW \qquad (6) \end{cases} \tag{3.13}$$

As a result of this optimization, every plane-set would become constrained by a hop number denoted by H. Constraint (1) represents the plane-constraint for all the topologies except for $T1M1$ and $T2M1$ which are strict trees. This means that only one plane is achieved under these two topologies. It is assumed that with higher number of planes and accordingly a higher number of paths, traffic can be better balanced. As stated earlier in section 3.2.3 and shown in [17] and [58], this assumption is wrong and 3-5 planes would be sufficient in achieving near-optimal performance. We considered a smaller upper bound (< 4) for $T1M2$ and $T2M2$ as a lower number of RPs with long redundant routes result due to lower meshing. Constraint (2) ensures that every node in the path is in the solution and has only one arc entering it. Constraint (3) states that only one arc enters a node in position h in any path and there is only one arc leaving that node in position $h+1$. Constraints (4) and (5) ensure that only one arc in position h enters the destination node for every demand in every path-set ρ_n^k. These two constraints guarantee the feasibility of the solution. Constraint (6) states that if $arc(u,v)$ is included in the solution, it exists in the path between the source and its corresponding destination node. It is notable that a decline in the number of planes to the desired range is acheived post hop-constraint. In our study, $X = 64$ results in the best set of RPs obtained under the tested topologies.

3.5.2 Quality of Plane-set (QoP)

QoP determines the quality of every set of RPs post construction based on some generic parameters. QoP also provides a comparative analysis in order to determine whether the hop-constraint which was introduced to select the optimal number of planes, improves the quality of the RPs. MPR based methods are also compared with the MPLS offline TE approach. In the latter case, the weight for every link was set to 1 and the same number of paths as the MPR constrained case were built for every demand simply by using hop-count increment to allow for the creation of L multiple paths. This approach aims to mimic the MPLS offline TE approach where multiple LSPs are built for every demand with a hop-count threshold while ensuring one node-disjoint path (or atleast a maximum number of nodes being disjoint if not all) [2]. The number of LSPs are set based on a set of given metrics as detailed in [2] (such as hop-threshold and a node-disjoint path) hence reducing the number of LSPs needed, obtaining as many as desired by the network planner. Accordingly, the metrics are set such that the same number of LSPs as the RPs in the MPR constrained case were obtained (i.e. equivalent to our optimum configuration). Henceforth for simplicity in formulation, N will also represent L number of LSPs ($L \equiv N$).

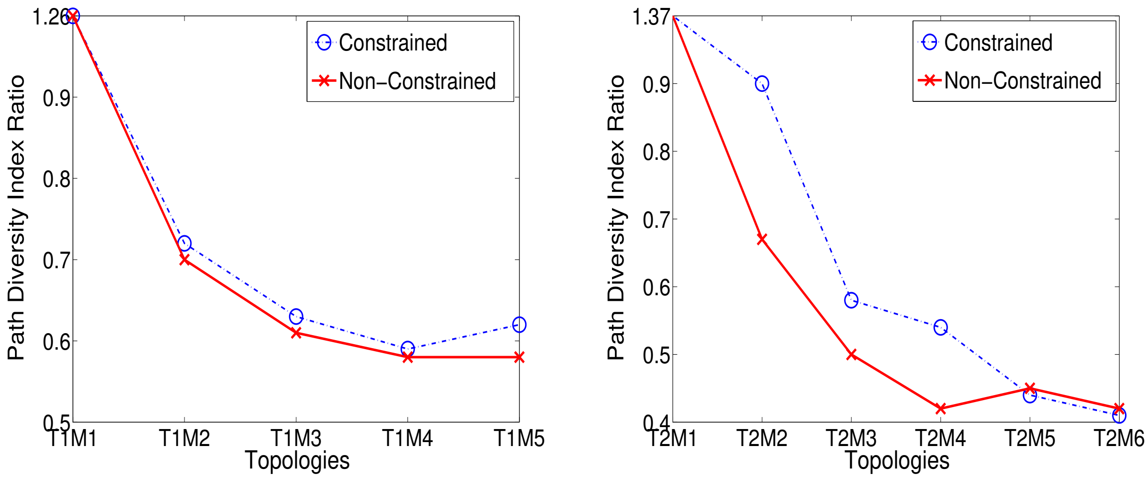
3.6 Performance Evaluation

3.6.1 Path Diversity Index Ratio (PDI Ratio)

PDI Ratio is defined as PDI across a set of available RPs relative to the maximum possible PDI across a set of available RPs under a given topology (PDI was introduced in subsection 3.4).

$$QoP \propto \frac{\sum_{d=1}^{D} \sum_{n=1}^{N} R^{d}_{eP^{d}_{n}}}{(\sum_{1}^{E} e).(|N-1|)} \tag{3.14}$$

PDI Ratio is indicative of how close to optimum (i.e. 1) our network is in terms of PDI. Figure 3.2 shows that PDI is generally closer to optimum with a lower number of available RPs (as it is the case post-constraint) for most of the topologies. There is an exception in case of $T1M1$ and $T2M1$ (strict trees) where the PDI Ratio is higher than optimum as more links get over-utilized relative to the only available RP. We haven't included MPLS in Figure 3.2 as the MPLS method does not consider path diversity in building multiple LSPs to obtain a balanced link usage distribution (hence there is no optimum to compare against). In fact, the absence of path diversity in the MPLS case leads to some links ending up not being used, putting a burden on other links. From a network planning perspective; as explicit routing (pre-defined routes for every demand) is applied in both MPR and MPLS, the imbalance of link usage in case of MPLS in the offline mode will lead to a higher maximum link utilization when traffic flows in the network with certain links getting congested quicker. The average maximum LSP occupation of a link was measured as $|1.07 \times N|$ and $|1.13 \times N|$ $(L \equiv N)$ throughout the first and second set of topologies respectively as opposed to the maximum $|N-1|$ in the MPR case for both cases.



(a) (b)

Figure 3.2: (a) PDI Ratio for the 1st set of topologies, (b) PDI Ratio for the 2nd set of topologies

3.6.2 Reliability

If failure is associated with some probability p, assuming failures are independent and equal for all the links, the probability of a path with h arcs being operational is given by $(1-p)^h$ [92]. The links would also get penalized if included in more than one plane or overlapp with more than one LSP path. Consequently, the overall reliability per demand across a set of available independent planes associated with QoP can be derived as follows:

$$QoP \propto \sum_{d=1}^{D} \frac{1}{N} \left(\sum_{n=1}^{N} \prod_{h=1}^{H_n^d} (1-p)^{\sum_{n=1}^{N} R^d_{eP^d_n}} \right) \tag{3.15}$$

It is easy to conclude that every individual path in one plane with a lower hop-count would have a higher reliability. Figure 3.3 demonstrates the reliability indicator for all the demands across the total available RPs being higher post-constraint, which is due to shorter paths in terms of hop-count. The reliability in case of the MPLS method is consistently lower as compared to the MPR constrained case (where the number of LSPs and RPs built are equivalent), mainly due to more links having been overused and hence penalized further throughout the constructed LSP paths. The results obtained in Figure 3.3 are based on a set of distinct probabilities of failure being randomly distributed among the links.

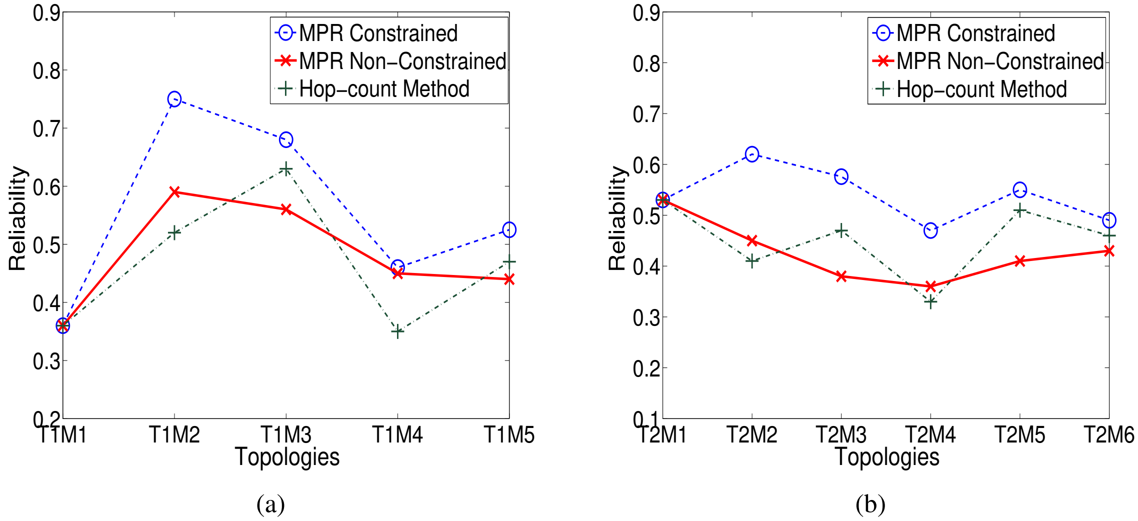
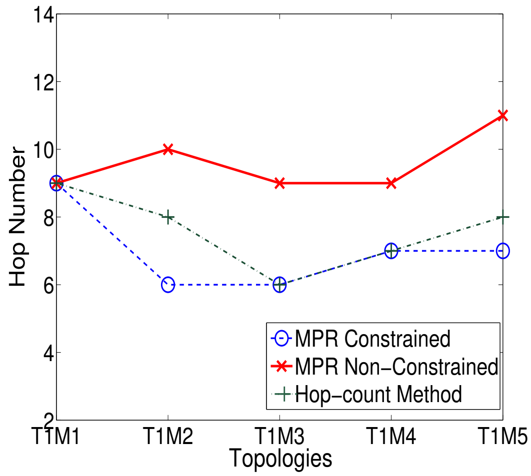


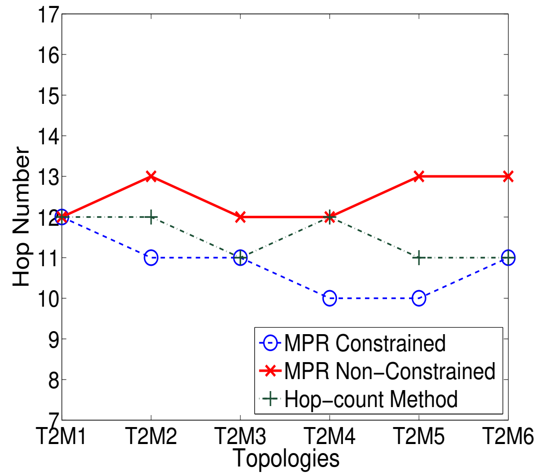
Figure 3.3: (a) Total per-demand reliability indicator for the 1st set of topologies, (b) Total per-demand reliability indicator for the 2nd set of topologies

3.6.3 Hop-count

As reflected in Figure 3.4, the maximum hop-count per plane-set across all the demands would decline as a result of hop-constraint. It can be also observed that lower number of hops are transversed in the MPR constrained case compared to the MPLS case. The maximum hop-count represents the worst case of path length in a topology among the RPs. The maximum path length for the MPLS method is indicative of the maximum hops needed to build multiple LSP paths per demand.



(a)



(b)

Figure 3.4: (a) The maximum hop number for the 1st set of topologies, (b) The maximum hop number for the 2nd set of topologies

3.7 Summary

In this chapter, the extension of MPR in all-IP access networks has been investigated. The trend towards a flat-IP structure, reflected through the expected direct IP connectivity between the base stations, demands a new routing mechanism. This mechanism allows the network to maintain several independent logical topologies which can be used to balance the traffic load in the network.

Hop-constraint was introduced in order to select a set of RPs, resulting in an desirably configured network. Moreover, QoP has been proposed to gauge the quality of the RPs in terms of various metrics in the offline mode. With this approach, the number of RPs has been kept to the desirable level despite of having a higher number of sources and destinations. Moreover, the reliability indicator and the PDI Ratio have increased by 21% and 10% on average, respectively. Our MPR-based approach has also shown enhancement over the MPLS approach.

In the next chapter, MPR's offline TE analytical model will be expanded and presented as being the generalization of the minimum set cover problem accordingly. In addition, MPR's online TE mechanism will be extended to reflect two cases that represent the architectural evolution of access networks. The varying internal/external traffic distribution will underpin this analysis under different criteria for the purpose of comprehensiveness. MPR will also be compared against MPLS in terms of both offline and online metrics.

4

Practical Aspects of Multi-Plane Routing-based Load Balancing Approach for Future Link-State Convergent All-IP Access Networks

4.1 Introduction

With the expected surge in global IP traffic, service providers need to adapt accordingly to operate disruption and loss free networks supported with the developing IP infrastructure. As oulined in the preceding chapters, with the disposal of the hierarchical network structure, radio access networks are moving towards a flat-IP architecture and novel topological set-ups in the backhaul. Hence, a routing paradigm that employs suitable traffic engineering techniques aligned with the developing nature of future access networks must be applied. It becomes imperative that the routing considerations for IP access networks converge with the ones found in conventional intra-domain routing.

In this chapter, Multi-Plane Routing that consolidates various aspects of an all-IP infrastructure is extensively analyzed in access network structures. In the previous chapter, MPR's offline algorithm was evaluated and extended to become adaptive to the changing access networks architectures. In this chapter, we extend our study to expand upon the offline approach and include an extended online algorithm to propose a MPR-based TE approach considering two different scenarios in order to reflect the evolution in the architectural design of access network structures. Our study considers a realistic traffic scenario with a varying range of internal/external traffic for the purpose of comprehensiveness and practicality. Moreover, a new optimization framework for the offline and online TE mechanisms of MPR have been formulated. Accordingly, a practical performance evaluation testing the validity of the aforementioned scenarios is presented. Our simulation results demonstrate extensive analysis in terms of several performance criteria in networks. It is convincingly shown that for ranges of topologies, MPR's utilization of the whole topology in building path diversity in networks allows for significant improvement of networks capacity, performance and support for meshing.

4.2 Discussion on the Investigated Practicality

The structure of IP access networks calls for new considerations in IP-routing mainly due to tree-like topologies. Access networks are generally comprised of a transit routing space that connects the access nodes to the core network through a gateway. Traffic flows between the gateway and access nodes in both directions, and between access nodes. Such access network structures are necessitated by the practical requirements of deployments. These requirements dictate network planning to conform with diverse topological layouts of heterogeneous access points and deployed infrastructures. In the recent evolution of networks [30], randomness of topological layouts imposes novel challenges for TE due to expected capacity constraints in backhaul links of interconnected femto, pico, micro and macro accesses. Furthermore, novel user mobility models have emerged for these network access structures aligned with the 5G development [93].

A reference scenario was studied for MPR in [60] and [21] where the RP structure's construct was such that only dedicated RPs (i.e. paths) for every *Gateway (GW)-Aggregation Router (AR)* pair were considered. Under this scenario, the GW was considered to be the only possible anchoring point of traffic in the network, hence, the bulk of traffic in the network would have been of a downlink nature. Moreover, all the traffic was assumed to be external (i.e. have emanated externally) with the possible existence of internal traffic between the ARs being neglected. We extend and complete the analysis of MPR in access network structures by studying and comparing two cases considering the existence of both internal and external traffic (with both uplink and downlink flows) with the possibility of all the ARs and the GW being sources and destinations of traffic:

- Case I: The RP structure is comprised of multiple *GW-AR* pairs. This design concept is restricted to 3G environment's architectural functionality where the entire traffic destined for outside of the network towards the big Internet and the internal traffic between the ARs would pass through the GW. We are targeting to expand this model to converge the Internet routing and future cellular systems' requirements by modifying the RP structure, allowing for direct communication between the ARs as reflected in the design concept for Case II.

- Case II: In this case, the RP structure is modified by including direct communication paths between ARs in addition to the duplex *GW-AR* pair, hence deploying the IGP's operation in full (i.e. OSPF). Our design concept is equally reflected in the trends towards a flat-IP structure in cellular networks where the increasing need for such structure has been emphasized [9] [94]. Accordingly, base stations are directly interconnected by IP and the forwarding domain barriers in these networks (i.e. radio access and core networks) are being abolished making the new backhaul connection space open to diversification of paths via meshed hierarchical topological set-ups. In fact, with the expected increase in the backhaul traffic [56], the wired backhaul links' overload could be alleviated by the diversity offered by MPR [30].

4.2.1 Elaboration of Novelty

This chapter contains the following contributions:

- We revisit the multi-topology (i.e. RPs) construction problem in intra-domain networks. To this end, we prove MPR's offline RP construction problem as being the generalization of the minimum set cover problem which is NP and also NP-complete. Hence, the adoption of heuristics to solve such a problem is justified.

- We present optimization frameworks that formally describe the offline and online TE mechanisms of MPR. First, by leveraging the initial offline TE model for multi-topology construction [18] that was built upon in the initial MPR [17], we combine our approaches to the offline TE in [19] and [20] to enable hop-constrained path diversity across various topologies. Moreover, since we take into account an increased pairing of traffic sources and sinks, we design a corresponding new online TE model based on a multicommodity flow problem associated with different classes of flow demands.

- A thorough performance analysis of MPR is conducted investigating: i) diverse ranges of topologies and meshings; ii) realistic traffic scenarios with varying ratios of internal and external traffic; iii) traffic of both uplink and downlink nature, where all the ARs and the GW can be *Ingress/Egress*. This extends the performance analysis of [20] where a single topology was examined, hence providing novel and more concrete conclusions compared to the first analysis of the early versions of MPR [21] (i.e. GW anchored traffic distribution scenario). To the best of our knowledge, such a thorough practical analysis that facilitates a comprehensive vision of the network's performance is absent in literature. We conclude by recommending our analytical strategy for the study of other load balancing approaches.

- To reinforce the practicality of our study, we conduct analyses of MPR in Case I alongside Case II. This looks forth to the architectural evolution of cellular and Internet-based access networks identifying the case with superior performance. To the best of our knowledge, despite research having looked into the underlying standards supporting flat-IP, the validity of such a design concept has not been studied previously. To this end, the emerging utilisation of such IP-enabled direct communication is accommodated in our investigation.

- Finally, MPR's offline and online TE approaches are compared against that of MPLS which acts as it main rival in access network structures. In this context, the reliability of the aforementioned approaches is also evaluated.

4.3 System Model

4.3.1 Underlying Concepts

As stated in the preceding chapters, MPR divides the physical topology into multiple logical planes called RPs. Each RP embodies an instance of OSPF associated with a dedicated link weight setup and it can overlap with another or share any subset of the underlying network [1]. MPR applies path diversity in building RPs using an offline algorithm that leads to the full utilization of resources (i.e. links) in the network. All the routers will have different Routing Information Bases (RIBs) (i.e. control plane) and Forwarding Information Bases (FIBs) (i.e. data plane) through which routes are defined in every RP. It is notable that each RIB/FIB represents one RP. MPR is originally envisioned to exploit the bits available in the Type of Service (ToS) field of IP packets, specifically, DiffServ integrated bits. DiffServ, that was put forward by the IETF in [95], is designed to facilitate multiple requisite QoS in the network and it supersedes the obsolete Type of Service (ToS) field whose bits are re-branded in DiffServ. Hence, in case DiffServ is used, there would be three unused bits (the fifth, sixth and seventh precedences) that can be used by MPR to mark each plane allowing up to 8 RPs to be supported. In case DiffServ is not used, MPR would have access to more bits, hence, more planes could be supported by

[1] We do not exclude the possibility of equal-cost multi-paths (ECMPs) occurring in the OSFP configuration of a RP. Regardless, each RP is used as one independent path diversity option from the *Ingress* to the *Egress*

ToS field (same or extended availability applies for IPv6 headers). Routers are configured to recognize the RPs through the unused bits. It was shown in [17] that up to 5 RPs are sufficient in case of MPR for similar network topologies as also substantiated in [58] for MT-OSPF. Consequently, MPR can exploit the structure in the IP header without imposing extra overhead onto each packet. This is opposed to MPLS where a 32-bit MPLS label stack is imposed on the IP packet by encapsulation causing overhead and router's configuration complexity.

MPR does not impede IP host mobility management solutions in IP access networks, neither end-to-end mobility (i.e. mobile IP) nor uses of mobility agents in access networks. MPR's routing solution runs separately from the mobility management functions such as tunnelling and IP address allocations. Since MPR also supports internal traffic as proposed in this thesis, when mobility agents are used, traffic to and from them is subject to regular decisions of the MPR's online algorithm at the *Ingress* points. Hence, MPR supports any location of mobility agents in access networks. Traffic load balancing with MPR's online algorithm can coexist with load balancing solutions via mobility agents in similar access network topologies [96]. In case of the projected user mobility model for future 5G networks [93] that include coverage of heterogeneous cells, MPR would treat the occurrences of varying traffic from mobile users as a uniform scenario at the network layer. To this end, MPR's online TE model is expected to adapt accordingly as to cease up the routing resources/paths in the whole topology caused by the unbalanced traffic injection to and from the *Ingress* aggregation router(s) (i.e. serving cell(s)).

4.3.2 Investigated Network Model

The network in Figure 4.1 represents an Autonomous System (AS) which constitutes a metropolitan or campus access network with a single gateway towards the big Internet. A common destination behind several egresses (in our case, multiple gateways) injecting into the Border Gateway Protocol (BGP) domain (i.e. inter-domain) has been identified as a solution to handle multiple egresses [97]. This reference fat-tree model is based on [23] where a meshed

Table 4.1: Setup of the topologies

Topo	Nodes	ARs	Links	Avg. Node degree	Total capacity (Gb)	No. of RPs
T_1M_1	19	6	32	3.36	11.94	4
T_1M_2	19	6	41	4.32	15.34	5
T_2M_1	32	14	53	3.31	15.28	3
T_2M_2	32	14	67	4.19	18.40	5

tree-based structure design has been suggested over other architectural designs as networks will have a significantly larger number of base stations and a much higher bandwidth demand at their edges (i.e. access points). Table 4.1 presents the specifications of the set of topologies of different meshings. Nodes are considered to be interconnected by wired Ethernet links. A $M/M/1$ queuing model is considered for every node. Topology 1 (i.e. T_1M_1 and T_1M_2) consists of 6 base stations acting as Aggregation Routers (ARs). Link capacities are randomly set up following a uniform distribution in [360, 400] for Level 1, [200, 240] for Level 2, [140, 180] for Level 3 and [60, 100] for Level 4 in the first topology studied (19 nodes). The second network studied (32 nodes) (i.e. T_2M_1 and T_2M_2) contains 14 ARs that are randomly distributed in the network as opposed to being strictly placed at the edge to provide more random configurations of networks. This topology is comprised of five levels where link capacities are generated in the following intervals: [360, 400] for Level 1, [160, 200] for Level 2, [110, 150] for Level 3 and 4, and finally [50, 90] for Level 5.

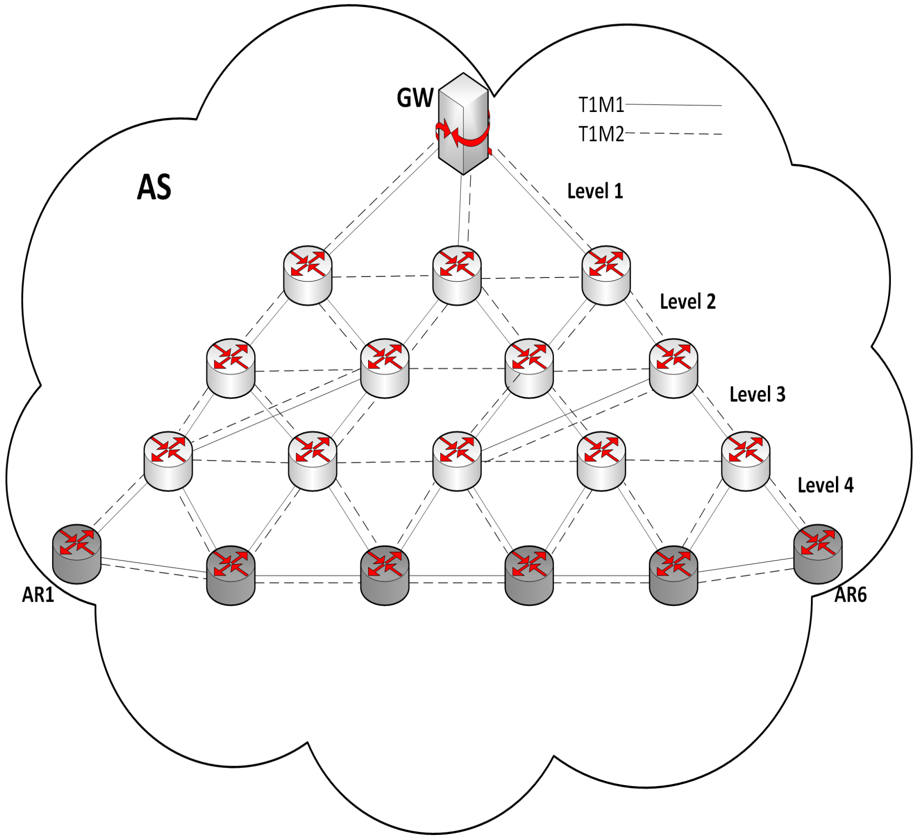


Figure 4.1: Autonomous system comprised of 19 nodes and 32/41 links. Average node degree: 3.36/4.32. Total capacity (Gb): 11.94/15.34 (T_1 topologies are illustrated, Table 4.1)

4.4 Analytical Model

4.4.1 Graph Theoretical Representation

Table 4.2 summarizes the important notations used in this chapter. The set of paths $(\rho_n^1, \rho_n^2, \ldots, \rho_n^K, \rho_n^{K+1})$ for all the ARs and GW amalgamate to represent one RP. ϑ=$\{\theta : \theta = 1, \ldots, \Theta\}$ signifies the source and destination pairs of traffic in the network (i.e. *Ingress* and *Egress* points) also called commodities. Case I and Case II were outlined in Section 4.2. In the

Table 4.2: Main parameter descriptions

Notation	Description
$\mathcal{V}$	Set of nodes. $\mathcal{V}$=$\{v : v = 1,...,V\}$
$\mathcal{E}$	Set of links. $\mathcal{E}$=$\{e : e = 1,...,E\}$
$\mathcal{N}$	Set of Routing Planes (RPs). $\mathcal{N} : n = 1,....,N$
$\mathcal{Z}$	Set of Label-Switched Paths (LSPs). $\mathcal{Z} : z = 1,....,Z$
$\mathcal{D}$	Set of demands. $\mathcal{D}$=$\{d : d = 1,...,D\}$
$\mathcal{H}_n^d$	Set of hops. $\mathcal{H}$=$\{h : h = 1,...,H_n^d\}$
$\mathcal{B}$	Number of Users. $\mathcal{B} = \{b : b = 1,...,B\}$
ϑ	Set of commodities. $\vartheta : \theta = 1,...,\Theta$
$\rho_{\mathcal{N}}^{\mathcal{K}}$	Set of paths containing path (i.e. $P_{\mathcal{N}}^{\mathcal{D}}$) set
$\mathcal{Q}$	Set of sessions. $\mathcal{Q} = \{q : q = 1,...,Q\}$
Γ	Set of weights for each constraint. $(\Gamma : \gamma = \gamma_0, \gamma_1 ..., \gamma_k)$
$\mathcal{T}$	Set of traffic types $\mathcal{T} = \{t : t = 1,...,T\}$
$\Pi^{b,d}$	Traffic rate associated with user u and demand d
m_q	Additive QoS metrics associated with session q
c_q^t	QoS constraint of session q associated with traffic type t
$\varphi_\Gamma^t(p_n^d)$	Cost of a path associated with a RP for traffic type t
$C(b(p_n^d))$	Link capacity of the least available bandwidth on path p_n^d

first case where all the traffic travels through the core, path set ρ_n^k is represented as follows:

$$\rho_n^k = \left\{ \begin{array}{ll} AR_{\mathcal{S}} \Leftrightarrow GW & : P_n^{d=1} \\ AR_{\mathcal{S}} \Leftrightarrow GW \Leftrightarrow AR_{fi} \neq AR_{\mathcal{S}} & : P_n^{d=2} \\ \vdots & \\ AR_{\mathcal{S}} \Leftrightarrow GW \Leftrightarrow AR_{la} \neq AR_{\mathcal{S}} & : P_n^{d=K} \end{array} \right\} \tag{4.1}$$

In the second case, path-set ρ_n^k is:

$$\rho_n^k = \left\{ \begin{array}{ll} AR_{\mathcal{S}} \Leftrightarrow GW & : P_n^{d=1} \\ AR_{\mathcal{S}} \Leftrightarrow AR_{fi} \neq AR_{\mathcal{S}} & : P_n^{d=2} \\ \vdots & \\ AR_{\mathcal{S}} \Leftrightarrow AR_{la} \neq AR_{\mathcal{S}} & : P_n^{d=K} \end{array} \right\} \tag{4.2}$$

Where $\Leftrightarrow$ represents a duplex path through other nodes. The GW-AR pair is reserved in every RP for the case that the desired destination address is located outside of the network and vice versa. $d = 1$ represents the GW-AR pair in path-set ρ_n^1 and the demand increments up to D that corresponds to the final *Ingress-Egress* pair in path-set ρ_n^{K+1}.

Every plane is a subset of the physical topology of the underlying network (i.e. uses all *Ingress*, *Egress* routers and a subset of the transit routers and links). A separate RIB/FIB is maintained for every subset/RP. For graph G, the sub-graph induced on a vertex subset/RP $\rho_n^{\mathcal{K}} \in G$ of V_G is denoted as $G(\rho_n^{\mathcal{K}})$.

$$\begin{cases} V_{G(\rho_n^{\mathcal{K}})} = \{u, v \in V_G | \exists e \in E_G\} \\ E_{G(\rho_n^{\mathcal{K}})} = \{e \in E_G | e = \langle u, v \rangle \;\; u, v \in V_G\} \end{cases} \tag{4.3}$$

4.4.2 Offline TE Approach

As stated earlier, the offline TE approach yields RPs that will integrate into a finite RP set as a pre-runtime path diversity network planning step of MPR. In this section, we will first prove the NP-completeness of RP construction and selection that justifies MPR's application of heuristics to this end. Subsequently, MPR's RP construction problem is formulated.

A Proof of NP-Completeness

As discussed earlier, MPR adapts the multi-topology OSPF approach in building multiple alternative paths between each source-destination pair through a network. MPR's offline algorithm is aimed at obtaining a set of RPs leading to the improvement of the projected link usage and path diversity in access networks. The prime objectives of the offline algorithm are as follows:

1. The aim is to obtain a set $\mathcal{N}$ of $|\mathcal{N}| = N$ RPs.

2. Each RP $n \in \mathcal{N}$ contains a valid path for every source-destination pair in the underlying network.

3. Every link in the underlying network topology appears in at least one of the constructed RPs in the set. This also implies that the union of the planes renders the underlying topology.

4. Every link in the network is used at most $N-1$ times.

5. The cost between every source-destination pair is minimum for each plane subject to the assigned link weights.

We demonstrate that the problem of interest, given the requirements stated above, is *NP*-complete. This is achieved herein by demonstrating that a well-known *NP*-complete problem is reducible, in polynomial time, to our problem. We commence this proof by summarizing the minimum set cover (MSC) and the minimum δ-set cover (δ-MSC) problems [98] below: [**Minimum Set Cover Problem**] Given a finite collection $\mathcal{S} = \{S_i\}_{i=1}^{I}$ of subsets of a universe U, a *set cover* $C \subseteq \mathcal{S}$ is a subcollection of the sets whose union is U (physical topology), i.e. $\bigcup_{S \in C} = U$. Moreover, each $S \in \mathcal{C}$ has an associated non-negative cost c_S. The minimum set cover problem is to compute such a subcollection $\mathcal{N} \subseteq \mathcal{C}$ such that it is a set cover for U and its cost $\sum_{S \in \mathcal{S}} c_S$ is simultaneously minimized. It is notable that each S_i represents a candidate RP.

[**Minimum δ-Set Cover Problem**] Assuming that instances of the weighted set cover are such that each $S_i \in \mathcal{S}$ has at most δ elements then we have the δ-set cover problem. Note that the unweighted set cover and unweighted δ-set cover problems are special cases of the weighted set cover and weighted δ-set cover problems, respectively. Furthermore, it is known that the MSC problem is *NP*-complete. To show that our problem is *NP*-complete it suffices to show that it is in *NP* and that the weighted MSC problem is reducible to our problem in polynomial time. Let the network topology being considered be defined by its connectivity graph $G = (\mathcal{V}, \mathcal{E})$ and its associated link weight function $w : \mathcal{E} \mapsto \mathbb{R}_+$, that assigns a non-negative weight $w(e)$ to each edge $e \in \mathcal{E}$. It is understood that $\mathcal{V}$ and $\mathcal{E}$ are the set of all vertices/nodes and edges/links respectively of the underlying network. Define $\mathcal{S}$ to be a collection of distinct subsets of $\mathcal{E}$, that is to say: $\mathcal{S} = \{S_i\}_{i=1}^{I}$ where $S_i \subset \mathcal{E}$ for each $i = 1, 2, \ldots, I$ so that for any $i \neq j$, $S_i \neq S_j$. Such a collection of subsets can be obtained, for example by constructing all spanning trees of the underlying graph G [99]. Each tree S_i is simply a subset with at least $\delta + 1$ elements in addition to the transit routers (that are not sources or destinations) (edges 'e') chosen from $\mathcal{E}$; with an associated cost $c_{S_i} = \sum_{e \in S_i} w(e)$. It is easy to see that $\bigcup_{\forall i} S_i = \mathcal{E}$. Now given $\mathcal{S}$, each element S_i of it has a path between all possible source-destination pairs and so it is a valid RP. However our task here is to find the subcollection $\mathcal{N}$ of RPs of minimal cost that utilizes every link in the network. In other words, we desire an $\mathcal{N}$ such that $\bigcup_{S_i \in \mathcal{N}} = U$ and $\sum_{S_i \in \mathcal{N}} c_{S_i}$ is minimized. This is clearly the minimum set cover problem, by definition. It is now clear that our MPR problem is a generalization of this MSC problem, therefore it is in NP and also NP-complete.

Problem Formulation

We introduce a modified offline TE approach that incorporates hop-constraint optimization to build and select RPs while ensuring diversity ahead of traffic flow into the network. When applying the previously proposed offline algorithm [21] to build RPs connecting the *Ingress-Egress* pairs, it is not guaranteed that the shortest possible RP set in terms of hop-count would be selected. Therefore, the resultant paths would render long routes in terms of hop-count specially in Case II where $AR - AR$ pairs are also connected directly. Under this case, some of these routes would pass through the gateway or through nodes located very high in the transit. This would not be desirable in our study to apply the MPR technique under the new scenario where access points communicate directly. We use hop-constraint to select a set of RPs that meet our RP-construction objectives while avoiding redundant paths. We have adopted the hop-constraint optimization which was originally introduced in [91] for spanning tree constructions. Here, we have added more constraints and have reformulated certain representations in order to adjust the optimization problem to our work. Weight of link e between any two nodes (u, v) in plane n is denoted by $w(n, e)$ (i.e. $e = arc(u, v)$). Link Usage (LU) represents the number of

RPs that include e in their shortest path across the given demands, which is defined as:

$$LU_e = \sum_{n \in \mathcal{N}} \sum_{d \in \mathcal{D}} R^d_{eP^d_n} \quad, \forall e \in \mathcal{E} \;\; and \;\; \forall d \in \mathcal{D} \tag{4.4}$$

The maximum LU on every link is $LU_e = N - 1$ as initially proposed in [17] to ensure Full Path Diversity (FPD). The link weight computation between nodes (u, v) corresponding to an iterative process of penalizing choices of links relative to previous RPs is given by equation 3.7 presented in Section 3.4 Three methods are integrated in weight configurations setups (i.e. equations 3.8-10) which consecutively penalize links in the previous RP, amalgamation of links in all preceding RPs and the most used links across RPs:

The link weight assignment calculates N set of positive link weights $W_n = \{w(n,e) : 1 \leq w(n,e) \leq Z, \forall n \in \mathcal{N}, \forall e \in \mathcal{E}\}$, and $Z(= 2^{16} - 1)$ as the highest value that OSPF can handle. More RPs will be tested with a higher value of X that ranges from 1 to X_{max} incremented by 1 with $X_{max} = \{2; 4; 8; 16; 32; 64\}$. $w(n,e)$ considers the involvement of a link in RP $N - 1$. The RP construction algorithm is iterative by nature.

We formulate MPR's offline approach as a constrained shortest path routing problem. This approach aims to minimize the chance that, for a given demand, all RPs share a single link and to maximize the possibility of any link being used in at least one RP ensuring a set of shortest possible paths concatenating to represent one RP, while also aiming to equivalently minimize $\sum_{e \in P^d_n} w(n,e)$ for every P^d_n. The decision variables are defined as followed: $R^d_{(uv)P^d_n}$ represents the binary directed variable which indicates whether $arc(u,v)$ lies in the minimal tree. Meanwhile, $Z^d_{(uv)P^d_n}$ is the directed binary flow variable that indicates whether $arc(u,v)$ lies in the only path from the *Ingress* t to the *Egress* node $s \in Egress$ at position h in RP n as presented in equation 3.11.

$$
\begin{aligned}
\min \quad & \sum_{n\in\mathcal{N}}\sum_{d\in\mathcal{D}}\sum_{(u,v)\varepsilon V} R^d_{(uv)P^d_n}.w(n,e) \\
\text{s.t.} \quad & \sum_{v:(u,v)\in\mathcal{E}} R^d_{(uv)P^d_n} - \sum_{v:(v,u)\in\mathcal{E}} R^d_{(vu)P^d_n} = \\
& \begin{cases} 1, \text{ for } u = s \\ 0, \text{ for } u \in V \setminus \{s,t\}, \\ -1, \text{ for } u = t \end{cases} && (a) \\
& 1 \le LU_e \le N-1 && (b) \\
& \sum_{(u)\varepsilon V} Z^d_{(uv)P^d_n} - \sum_{(u)\varepsilon V \neq t} Z^d_{(uv)P^d_n} = 0 \\
& \forall s, v\varepsilon V \neq AR_{\mathcal{S}}/GW, v \neq s && (c) \\
& \sum_{(u)\varepsilon V} Z^d_{(uv)P^d_n} = 1, \qquad \forall v\varepsilon V \neq AR_{\mathcal{S}}/GW && (d) \\
& \sum_{n\in\mathcal{N}}\sum_{d\in\mathcal{D}}\sum_{(u,v)\varepsilon\mathcal{E}} Z^d_{(uv)P^d_n} \le H.D.N && (e) \\
& Z^d_{(uv)P^d_n} \le R^d_{(uv)P^d_n}, \forall (u,v)\varepsilon E, s\varepsilon V \neq AR_{\mathcal{S}}/GW && (f) \\
& R^d_{(uv)P^d_n} = \{0,1\}, \forall (uv) \in \mathcal{E}, \forall d \in \mathcal{D}, \forall n \in \mathcal{N}
\end{aligned}
\tag{4.5}
$$

Where $H = \max_{d,n}\{H^n_d\}$ and demand d is such that it includes t as the *Ingress* node and s as the *Egress* node. This optimization problem ensures that there exist a set of independent loop-free least-cost path sets of the least possible number of hops with every link being used at least once and at most $N-1$ times (ensuring diversity). Our suggested modified approach defines a termination point in the iterative RP construction algorithm subject to the above optimization framework constraints as opposed to the previously proposed offline TE where no such constrained framework was set out. As a result of this optimization, every plane-set would become constrained by a hop number denoted by H (i.e. $\max_{d,n}\{H^n_d\}$) while ensuring diversity. As stated earlier in Section 4.3.1 and shown in [17] and [58], 3-5 planes would be sufficient in achieving near-optimal performance subject to topologies and meshing. Therefore, we control the hop-constrained iterative RP construction algorithm to allow for the construction of planes up to 6 depending on the topology and level of meshing. Constraint (a) ensures that every node in the path is in the solution and has only one arc entering it. Constraint (b) stipulates that every link will end up being used at-least once and at-most $N-1$ times ensuring diversity. Constraint (c) states that only one arc enters a node in position h in any path and there is only one arc leaving that node in position $h+1$. Constraints (d) and (e) ensure that only one arc in position h enters the destination node for every demand in every path-set ρ_n^k. These two constraints guarantee the feasibility of the solution. Constraint (f) states that if $arc(u,v)$ is included in the solution, it exists in the path between the source and its corresponding destination node. In our study, $X = 64$ in the weight function results in the best set of RPs obtained under the tested topologies.

4.4.3 Online TE Approach

Routing in a network can be represented as a multi-commodity flow problem with multiple flow demands associated with different *Ingress* and *Egress* nodes for each plane. A flow demand corresponds to IP sessions, and once a plane is chosen it remains unchanged for duration of the session.

$$\sum_{v:(u,v)\in\mathcal{E}} f^{\delta}_{(uv)P_n^d} - \sum_{v:(v,u)\in\mathcal{E}} f^{\delta}_{(vu)P_n^d} = \begin{cases} d_u^{\delta}, \text{ for } u = s \\ 0, \text{ for } u \in V - \{s,t\}, \\ -d_u^{\delta}, \text{ for } u = t \end{cases} \tag{4.6}$$

$$f_{uv} = \sum_{\delta\in\vartheta} f_{uv}^{\delta} \leq c_{uv} \qquad \forall (u,v) \in \mathcal{E} \tag{4.7}$$

$$f_{uv}^{\delta} \geq 0 \qquad \forall \delta \in \vartheta, \forall (u,v) \in \mathcal{E} \tag{4.8}$$

where d_u^{δ} represents the amount of traffic contributed to the network by node u for commodity δ. Equation (4.6) signifies the flow conversation constraints and (4.7) represents the capacity constraints. We keep the objective of achieving a practical maximum use of diverse network topological configurations/RPs facilitated by the offline algorithm. The options of paths subject to every RP layout are cumulatively considered through online decisions made at the *Ingress/source*. To this end, we consider the application of heuristics namely MPR and its extension QoS-aware MPR (QMPR) in a multi-commodity flow scenario. MPR's online TE approach was initially introduced in [60]. As opposed to the previously considered singular source case, we have adopted a realistic online traffic scenario where both the GW and the ARs can be sources and destinations of traffic simultaneously giving rise to the breakdown of traffic of an internal and external nature. Additionally, we put forward a more complete formulation of MPR's online routing complemented with an optimization framework.

In the network; a set of users is defined as $\mathcal{B} = \{b : b = 1,...,B\}$. $\mathcal{T} = \{t : t = 1,...,T\}$ indicates the set of traffic types. $\mathcal{Q} = \{q : q = 1,...,Q\}$ represents the set of sessions whereas m_q signifies the additive QoS metrics associated with every session q. c_q^t is defined as the QoS constraint of session q associated with traffic type t. $\Pi^{b,d}$ indicates the traffic rate associated with user b and demand d. $||\Pi^{b,d}||_0$ signifies the non-zero non-negative entries of $||\Pi^{b,d}||$. MPR applies a plane selection policy for each session to ensure a regulated traffic flow in the network. This policy is enforced by the sources (i.e. GW and ARs). In the case of MPR, the cost of RPs are solely determined based on the available bandwidth and if there is more than one RP available, one RP is selected randomly. In the case of QMPR, when a packet arrives at a source, the qualified RPs in terms of bandwidth are first picked out, subsequently the packet's classification gets verified and hence its associated Service Level Requirement (SLR) (i.e. jitter, latency, packet loss) is obtained based on which the plane selection policy is applied. Consequently, RPs that do not meet the required criteria for the concerned traffic class are pruned and the most suitable RP with the lowest cost is selected. At this stage, in case of the existence of more than one RP that meets the QoS criteria, the RP with the highest available bottleneck bandwidth is selected. In the case of both MPR and QMPR, once the qualified RP is selected, the packet is forwarded on the chosen RP followed by the rest of the packets of the session. The cost function for any path p_n^d is represented as follows as a summation of the real time costs of each link in the path:

$$\begin{aligned} \varphi_{\Gamma}^{t}(p_n^d) = \Psi. \sum\nolimits_{uv \in P_n^d} \sum\nolimits_{q \in Q} R_{uvP_n^d}^{d} \left(\frac{m_q(uv)}{c_q^t} \right) . \gamma_q \\ + Y. \left(\frac{b(p_n^d) - ||\Pi^{b,d}||_0}{C(b(p_n^d))} \right)^{-1} \end{aligned} \tag{4.9}$$

Where $\gamma_q \in [0,1]$ is the binary factor used to associate session q with its QoS requirements. $b(p_n^d)$ represents the available bandwidth on path p_n^d. The available bandwidth is calculated by taking into consideration the bottleneck on every path at various instances:

$$\begin{aligned} b(p_n^d) = & \min_{(e_{uv,n}) \in p_n^d} \quad b(e_{uv,n}) \\ \text{Where:} \quad & \{e_{uv} | (u,v) \in \mathcal{V}^2, \forall u \neq v, \forall n \in \mathcal{N}\} \\ & b(p_n^d) = \{b(e_{uv,n}) | (e_{uv,n}) \in p_n^d, \forall n \in \mathcal{N}\} \end{aligned} \tag{4.10}$$

Ψ is the binary factor which is 1 when any path p_n^d meets the minimum bottleneck requirement as outlined above. Y symbolises the binary variable which is equal to 1 in case of both the QoS and bottleneck requirements are met by one or more than one candidate RP hence the one with the highest bottleneck bandwidth is selected. We formulate our optimization problem based on the general OSPF TE optimization framework proposed in [100]. MPR's online TE aims to maximize throughput while routing the traffic through the optimum path taking into account the associated cost which is sought to be minimised along with the traffic rate on every path on the RP set available. Our MPR-based formulation takes into account the existence of different types of traffic in the network whereas access to multiple paths is facilitated through the offline RP construction TE approach.

$$
\begin{aligned}
\max \quad & \sum_{q \in Q} \alpha_q \Phi_q - \sum_{q \in Q} \sum_{p_n^d \varepsilon \rho_{\mathcal{N}}} \varphi_\Gamma^t(p_n^d) ||\Pi^{b,d}||_0 \\
\text{s.t.} \quad & ||\Pi^{b,d}||_0 \ \le \ b(p_n^d) \\
& m_q(p_n^d) \equiv \sum_{e_{u,v}, n \in p_n^d} m_q(e_{u,v}, n) \le c_q^t \\
& \forall d \in \mathcal{D}, \forall b \in \mathcal{B}, \forall n \in \mathcal{N}, \forall t \in \tau, \gamma_k \in [0,1]
\end{aligned}
\tag{4.11}
$$

Where throughput of session q associated with any user and demand on path p_n^d is: $\Phi_q = \sum_{p_n^d \varepsilon \rho_{\mathcal{N}}} ||\Pi^{b,d}||_0$. α_q represents the optimum path for every session considering its associated cost. The constraints ensure the validity of the path in terms of meeting the minimum bottleneck requirement in addition to the QoS requirements associated with the corresponding session.

Algorithm 2 Online Plane Selection Algorithm

1: **procedure** POLICY-PS
2: Packet arrives at $Ingress\ AR_a/GW$ destined for $Egress$
3: **If** $\Pi^{b,d}{}_0 \le b(p_n^d)$, for at least $n \in \mathcal{N}$ **then**
4: Admit the session
5: Conduct lookup for the associated traffic class $t \in \tau$
6: Ascertain QoS requirements c_q^t for traffic class t
7: Remove all RPs in $\mathcal{N}$ that do not satisfy SLRs for each $q \in Q$ and retrieve set $\mathcal{CP}$
8: Calculate cost for each RP

$$
\begin{aligned}
\varphi_\Gamma^t(p_{cp_i}^d) = \Psi . \sum_{uv \in P_n^d} \sum_{q \in Q} R_{uvP_n^d}^d \left(\frac{m_q(uv)}{c_q^t} \right) . \gamma_q \\
+ Y . \left(\frac{b(p_n^d) - ||\Pi^{b,d}||_0}{C(b(p_n^d))} \right)^{-1}
\end{aligned}
$$

9: Select RP cp_1 with the lowest cost φ_Γ^t for the incoming session given: $\varphi_\Gamma^t(cp_1) \le \varphi_\Gamma^t(cp_2) \le ... \le \varphi_\Gamma^t(N - \bar{\mathcal{CP}})$
10: **else** Reject session
11: **end if**
12: **end procedure**

4.5 Performance Evaluation

In this section, the performance of the routing schemes are presented and evaluated. Section 4.5.1 sets out the experiment settings. Performance under a simulation scenario with practical evaluation criteria is presented in Section 4.5.2. Section 4.5.3 encompasses comparisons against MPLS.

4.5.1 Experiment Settings

We evaluate our MPR-based framework using extensive packet level NS2-based simulations interfaced with Matlab. Sets of topologies to which different meshings are applied are used for our study (as presented in Table 4.1). Initially, the performance of different methodologies for varying internal/external traffic distributions under different scenarios (i.e. Case I & Case II as outlined in Section 4.2) are presented and evaluated. Subsequently, the performance of MPR and QMPR under different meshing scenarios is compared with MPLS. For both of the studies, legacy OSPF and the OSPF InvCap approaches are used as the baseline scenarios to compare against. It is important to note that the legacy OSPF method and the OSPF InvCap method are differentiated based on link weights set to 1 (hop-count based) and inverse capacity-based weight setting, respectively. It is notable that no significant differences were observed between the legacy OSPF and OSPF InvCap approaches as a result of the experiments conducted. Regarding the number of RPs needed, in earlier studies for MT-OSPF [58], it was concluded that overall near-optimal network performance in terms of cost and link utilization can be achieved with up to 3-5 RPs as also substantiated in [17] for MPR. Incoming sessions of different traffic classes (as represented in Table 4.3) are randomly generated. Sources and destinations of traffic and the duration of the corresponding flows are also randomly selected throughout the simulation time. As the simulation runs, traffic is generated with a decreasing session arrival time so as to load the network until congestion level. With a new session request at the source of traffic (i.e. an AR or the gateway) the latter checks for bandwidth availability on the set of potential path(s) to reach the destination, regardless of the method used (OSPF, InvCap, MPR, MPLS or QMPR). Given the link-state nature of the aforementioned TE strategies, ARs and the GW are aware of the traffic dynamics and the links' status in the network at different time frames. The traffic rate is increased by reducing inter-arrival times of sessions at the *Ingress*es over a simulated real time of 12 seconds. In the case of the T_1 topology the overall traffic volume in the network increases up to approximately 330 Mb/s, whereas in the case of the T_2 topology the traffic volume goes up to 480 Mb/s. Beyond these points, mainly between 11 and 12 seconds, the network becomes significantly congested and the packet rate drops. The same conditions are applied to Case I and Case II simulations.

Table 4.3: Traffic types[1] and associated QoS requirements.

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 1	Low (≈ 150 Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium (≈ 250 Kbps)	300 sec	4-5 s	*none*	5 %
Class 3	Low (≈ 128 Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High (≈ 500 Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low (≈ 100 Kbps)	90 sec	*no specific requirement*		

[1] Applications examples; Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

4.5.2 Performance under Realistic NS2-based Simulations

In this subsection, the performance of different methodologies for fluctuating internal/external traffic distribution under different scenarios (i.e. Case I & Case II as outlined in Section 4.2) are presented and analysed in terms of various metrics. This study corresponds to an analysis under a realistic traffic scenario with two cases that are reflective of the architectural evolution of access networks as discussed in section 4.2. MPR's offline TE is implemented through Matlab simulations to build RPs ahead of the traffic flow. NS2 simulations are then applied for the online TE mechanism for MPR and QMPR as described in Subsection 4.4.3 along with

OSPF/InvCap. Different metrics are analysed by being averaged over snapshots throughout the simulation time for different traffic percentage distributions.

Blocking Rate (%)

The blocking rate constitutes the number of sessions that have not been transmitted into the network in relation to the ones having been successfully delivered throughout the simulation time. Blocking occurs as the network becomes gradually congested leading to the obstruction of new sessions at *Ingress/source*. The rendered mean session blocking rate, as observed in Figure 4.2, is lower in Case II in comparison with Case I as the bottleneckness of the entire traffic traversing the GW has been avoided. The blocking rate for the MPR-based methods is lower due to higher path diversity as compared to the OSPF/InvCap methods where a much fewer number of paths are available. As compared with MPR, the blocking rate for QMPR is slightly higher in both Case I and II. This indicates that the enforced QoS requirements have rendered greater blocked traffic. Moreover, the mean blocking rate has consistently increased for all the methodologies across the topologies in line with the intensification of the internal traffic distribution. It can be also observed that blocking is generally higher in case of the second topology-set (i.e. T_2M_1, T_2M_2) as the traffic flow distribution is different. This is due to the comparatively higher traffic load on the network incurred by more traffic sources in spite of the larger network size. The blocking has declined across both of the topology-sets in line with the increase in meshing as a higher number of links and RPs become available in consequence, to route the traffic [2].

Packet Loss Rate (%)

Packet loss rate represents the number of packets having been dropped in relation to the ones having been successfully delivered throughout the simulation time. Packet loss occurs due to insufficient queue capacities caused by increasing congestion in the network. As observed in

[2]This behavior intuitively suggests that as networks become randomly larger in size and includes more traffic sources, the transient space should increase (routers and meshing) accordingly to accommodate the demands

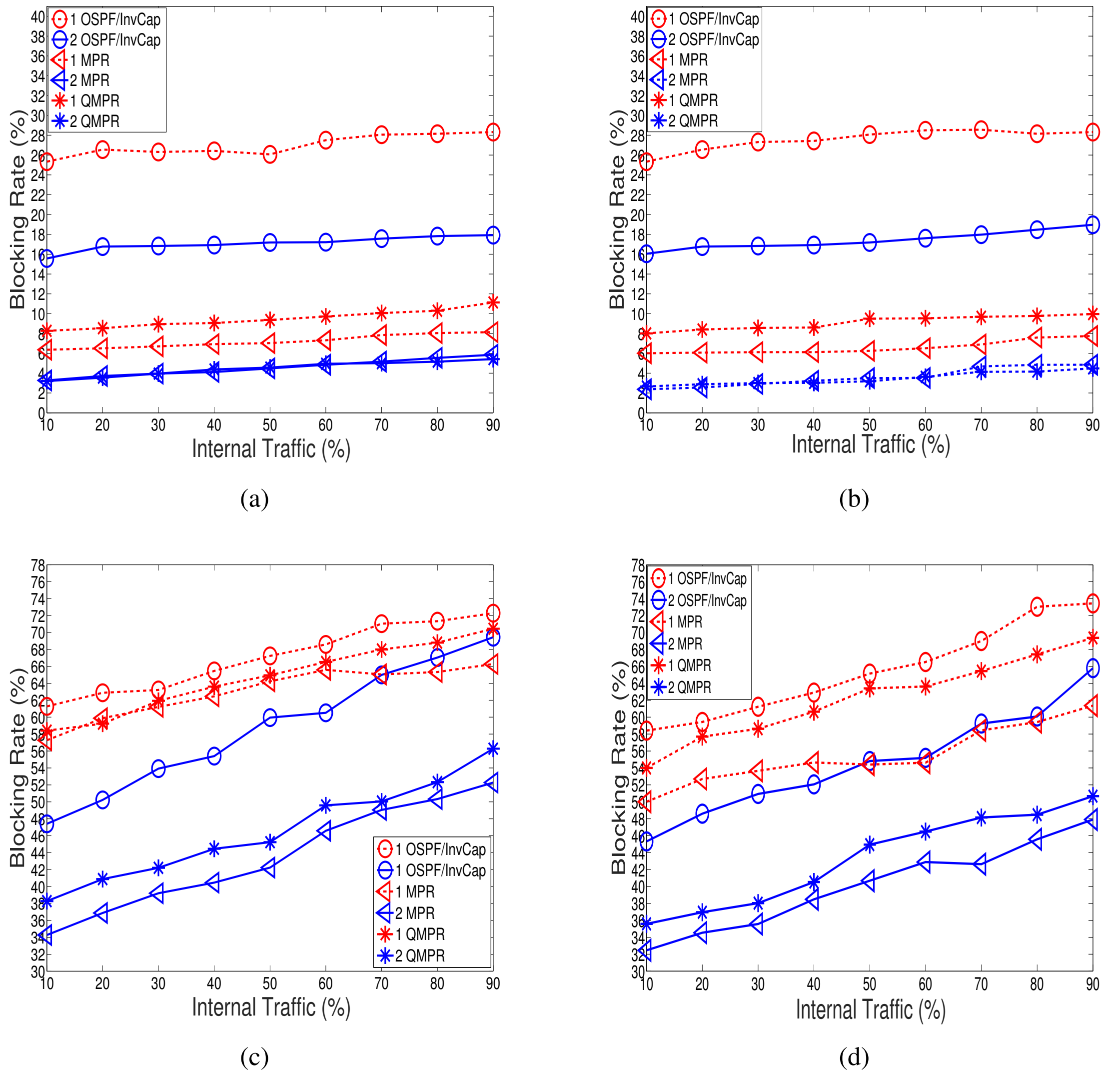


Figure 4.2: Blocking Rate (%); a) T_1M_1 b) T_1M_2 c) T_2M_1 d) T_2M_2

Figure 4.3, the rendered average packet loss rate is lower in Case II than Case I. This is due to higher congestion and blocking triggered by less path diversity for traffic sources in case I (where the entire traffic passes through the GW), having led to the loss of more packets. The loss rate in case of the MPR-based methods is lower due to the higher path diversity for the incoming sessions as compared with OSPF/InvCap. QMPR outperforms MPR in terms of loss rate as the packet distribution into the network is regulated based on the QoS requirements, hence resulting in a lower loss of sent packets. With the intensification of the internal traffic distribution, the loss rate has increased correspondingly across all the topologies. This is due to the higher congestion caused by the lack of residual capacity relative to the surging internal traffic demand throughout the network. It can be also observed that the packet loss rate declines as the meshing increases across both of the topology-sets since more links and RPs become available with the rise in meshing. Moreover, a generally higher loss rate has occurred in case of the second topology in which the traffic flow distribution model is different due to the comparatively higher traffic load on the network incurred by more traffic sources.

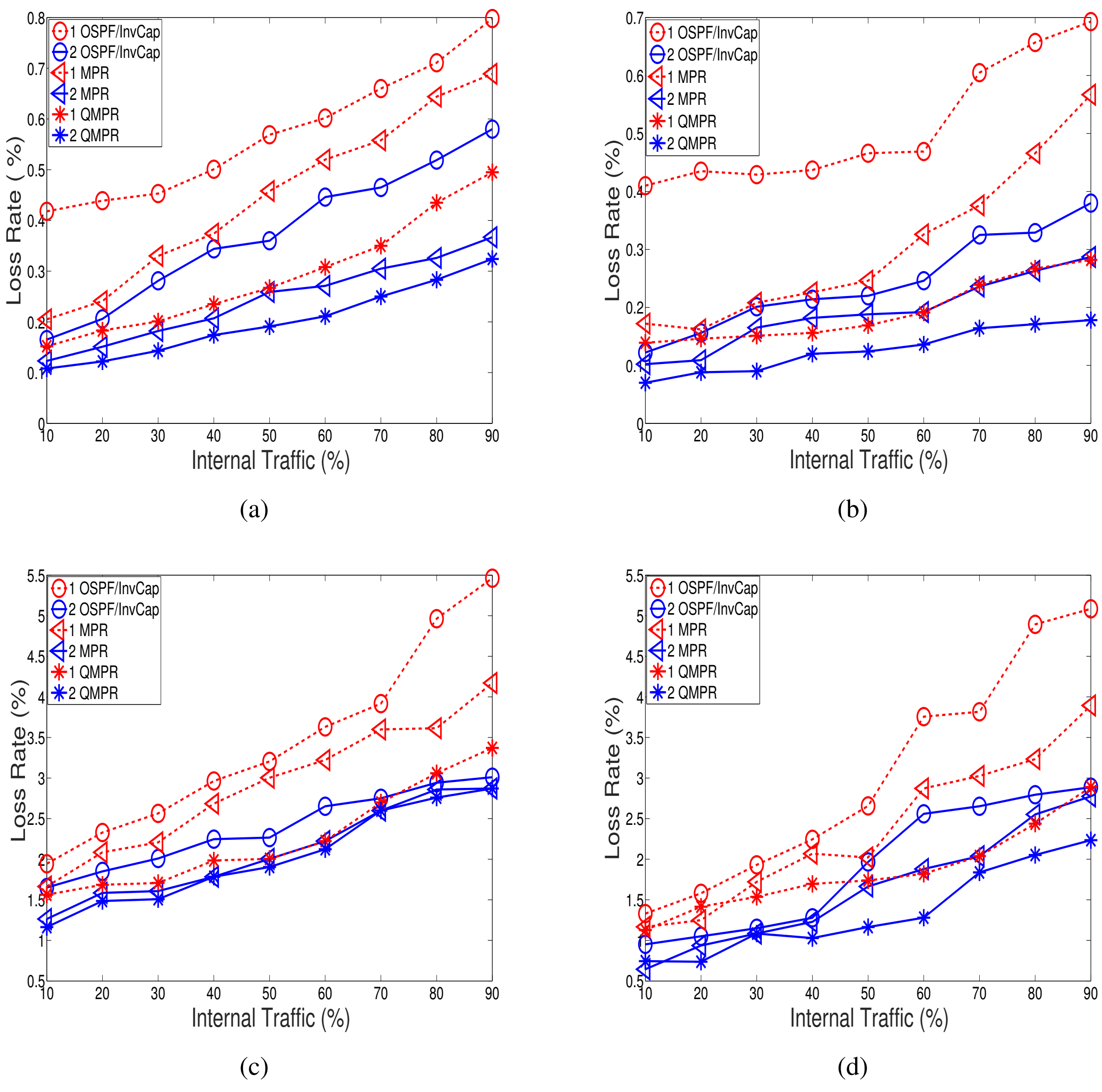


Figure 4.3: Packet Loss Rate; a) T_1M_1 b) T_1M_2 c) T_2M_1 d) T_2M_2

Delay (ms)

As can be observed from Table 4.4 and Table 4.5, a higher mean delay is incurred with Case I as longer routes are traversed as compared to Case II. Furthermore, a lower queuing delay occurs in case II due to the higher path diversity available for sources of traffic as opposed to Case I where the entire traffic passes through the GW. This leads to the accelerated queue processing in Case II. A higher delay is incurred in the MPR-based methods as shortest-hop routes are not always used and more traffic is delivered. It was shown in [100] that for OSPF TE, the price for a higher throughput facilitated by multiple available paths is the heightened average delay caused by growth in the average path length. It was also shown in [101] that as demand surpasses a certain amount, delay would be correspondingly higher as more traffic is delivered in the case of multi-path routing. Moreover, in both cases, delay has increased with the rise in the internal traffic distribution. This is the consequence of the higher traffic density having led to longer queue processing times, and a higher overall number of hops having been traversed. It can be also observed that the delay in the case of the second set of topologies is higher, as the network is larger in terms of nodes and links, with a higher traffic density. The results demonstrate a general decline in delay in line with the rise in meshing across both of the topology-sets. This is thanks to the availability of more links and RPs helping to lower the congestion in the network, in consideration of the average delay on every link being largely dependent on its residual capacity based on the well-known Kleinrock independence approximation [102]. Therefore, it can be concluded that the increase in meshing facilitates a better distribution of traffic and a consequential reduction in queuing times that results in a lower overall delay.

Throughput (Mb/s)

Table 4.6 and Table 4.7 represent the achieved network's mean throughput under varying traffic percentages. As observed, the achieved mean throughput is generally higher in Case II for different routing strategies as compared with Case I. This can be explained by the higher path diversity available in Case II resulting in larger amount of data being delivered. The MPR-based methods outperform OSPF/InvCap as traffic can be split over several paths in the case of MPR, leading to improved load balancing in the network and increased packet delivery correspondingly. The average of the overall achieved throughput for both cases has declined with the rise in the internal traffic distribution aligned with the surge in blocking. Additionally, it can be observed that throughput has risen in line with the increase in meshing as the session blocking rate has declined correspondingly for both topology-sets. It can be also observed that a generally higher throughput has been achieved in the case of the second topology-set where more traffic gets injected into the network.

Maximum Link Utilization (MLU)

As observed from Table 4.8 and Table 4.9, the MLU is lower in Case II as compared to case I, which is due to better traffic distribution as opposed to Case I where all the traffic traverses the GW. The resulting MLU does not exhibit much variation for different traffic distributions since the total average MLU for the entire network is expected to be almost consistent, without much variation, for the entire traffic under different routing strategies. MLU is lower for the MPR-based methods as expected due to the availability of multiple paths as compared to legacy OSPF/InvCap. Compared with MPR, QMPR has achieved a lower MLU as traffic is engineered based on QoS requirements resulting in less traffic flowing in the network. It is also observable that MLU has increased in line with the rise in meshing across the topologies. This is due to the higher amount of injected traffic into the second topology, in consideration of a lower number of available RPs relative to the existing number of links, leading to certain links being used more than before in line with the increased meshing.

4.5.3 MPR vs. MPLS

MPR's advantages over MPLS were discussed in Section 2.5. Additionally, it is important to note that as opposed to MPLS where only end to end pairs connected through LSPs (i.e.

Table 4.4: Delay (ms) for the first topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2
10	4.82	4.82	3.94	3.94	12.01	10.03	10.00	9.65	11.26	9.96	10.06	7.06
20	5.03	5.03	4.03	4.03	12.22	10.27	10.46	9.74	11.70	10.20	10.38	7.37
30	5.23	5.23	4.11	4.11	12.63	10.54	11.01	10.04	11.84	10.22	10.49	7.49
40	5.43	5.43	4.32	4.32	12.81	10.76	11.22	10.26	12.01	10.27	10.65	7.65
50	5.46	5.46	4.56	4.56	13.39	11.47	11.56	10.47	12.21	10.30	10.89	7.89
60	5.92	5.92	4.78	4.78	13.56	11.62	11.84	10.95	12.55	10.35	10.10	8.10
70	6.01	6.01	4.80	4.80	13.75	11.85	12.41	11.01	12.86	10.52	10.35	8.35
80	6.54	6.54	4.85	4.85	13.96	11.95	12.21	11.20	12.94	10.88	10.54	8.54
90	6.84	6.84	4.87	4.87	15.02	12.02	12.56	11.37	13.59	11.03	10.83	8.83

Table 4.5: Delay (ms) for the second topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2
10	81	81	48	48	159.8	152.1	109.4	100.5	138.5	129.5	92.5	80.1
20	81.4	81.4	48.3	48.3	160.4	152.8	109.6	100.5	139.8	129.8	92.8	80.8
30	81.8	81.8	48.8	48.8	161.3	153.1	110	100.6	140	130	93	81
40	82.3	82.3	49	49	162	153.8	110.3	100.6	140.5	130.6	93.1	81.2
50	82.7	82.7	49.3	49.3	162.7	154.2	110.8	101.1	140.8	131	93.4	81.6
60	83	83	49.7	49.7	163.6	154.8	111	101.3	141.3	131.2	93.8	81.7
70	83.5	83.5	50	50	164.7	155	111.3	101.7	141.7	131.9	94.1	82
80	83.8	83.8	50.2	50.2	165.3	155.7	111.8	102	142.3	132.2	94.5	82.7
90	84.2	84.2	50.4	50.4	165.9	156.3	112	102.1	142.8	132.8	95.3	82.9

Table 4.6: Throughput (Mb/s) for the first topology

Traffic	OSPF/InvCap				MPR				QMPR			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2
10	30.01	30.01	26.86	26.74	40.37	50.28	51.82	58.14	40.25	48.30	48.78	55.84
20	29.92	29.92	26.52	26.45	40.35	50.21	51.25	57.62	40.2	48.16	48.21	55.82
30	29.92	29.92	26.49	26.39	40.48	50.50	50.87	57.60	40.29	48.1	47.92	55.74
40	29.88	29.88	26.44	26.37	40.26	49.91	50.39	57.40	40.17	47.93	47.54	55.61
50	29.82	29.82	26.4	26.3	40.18	49.81	50.12	57.03	40.16	47.39	47.11	54.81
60	29.77	29.77	26.35	26.28	40.12	49.49	49.15	56.43	40.07	46.9	48.49	54.62
70	29.61	29.61	26.32	26.22	40.9	49.38	49.06	56.53	40.03	46.92	46.82	54.47
80	29.59	29.59	26.29	26.18	40.42	49.26	48.73	56.11	40	46.51	46.68	54.22
90	29.47	29.47	26.18	26.12	40.29	48.8	48.65	56.04	39.95	46.19	46.57	54.03

Table 4.7: Throughput (Mb/s) for the second topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2
10	31.29	31.29	47.44	47.44	47.44	52.52	102.2	120	42.84	48.52	97.39	115
20	31.26	31.26	47.15	47.15	47.15	52.53	102.1	120.3	42.45	48.53	96.34	115
30	31.15	31.15	47.02	47.02	46.18	52.43	101.1	120.8	42.18	48.43	97.84	115.7
40	30.30	30.30	46.51	46.51	46.63	51.61	100.5	120.1	42.51	47.61	96.35	114
50	30.08	30.08	46.24	46.24	45.24	51.46	100.5	119.5	42.14	46.63	97.36	114.4
60	30.18	30.18	46.44	46.44	45.39	50.54	100.4	118.7	41.44	46.54	96.19	113.3
70	30.19	30.19	46.14	46.14	45.24	50.70	100.2	116.2	41.44	46.21	96.65	113.1
80	30.07	30.07	45.21	45.21	45.21	50.34	99.83	114.9	41.21	44.54	96.14	112.6
90	30.04	30.04	44.08	44.08	45.08	50.15	99.45	113.2	41.08	42.15	96.61	112.3

Table 4.8: Maximum link utilization for the first topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2	T_1M_1	T_1M_2
10	0.708	0.784	0.683	0.704	0.689	0.704	0.595	0.619	0.637	0.641	0.564	0.578
20	0.711	0.786	0.686	0.706	0.691	0.700	0.587	0.616	0.635	0.642	0.565	0.576
30	0.709	0.786	0.686	0.706	0.689	0.704	0.586	0.617	0.635	0.642	0.564	0.578
40	0.712	0.785	0.685	0.705	0.693	0.708	0.593	0.614	0.637	0.639	0.565	0.576
50	0.711	0.787	0.687	0.707	0.693	0.708	0.593	0.619	0.637	0.639	0.562	0.577
60	0.710	0.786	0.686	0.706	0.681	0.700	0.589	0.610	0.641	0.639	0.564	0.577
70	0.710	0.788	0.688	0.708	0.690	0.704	0.586	0.611	0.640	0.641	0.562	0.576
80	0.709	0.788	0.686	0.708	0.693	0.704	0.590	0.620	0.639	0.642	0.562	0.574
90	0.713	0.789	0.689	0.709	0.689	0.703	0.588	0.615	0.636	0.639	0.561	0.575

Table 4.9: Maximum link utilization for the second topology

Traffic	**OSPF/InvCap**				**MPR**				**QMPR**			
(%)	Case I		Case II		Case I		Case II		Case I		Case II	
	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2	T_2M_1	T_2M_2
10	0.879	0.879	0.807	0.807	0.803	0.823	0.713	0.758	0.753	0.783	0.683	0.727
20	0.879	0.879	0.809	0.809	0.802	0.821	0.712	0.755	0.752	0.781	0.683	0.739
30	0.882	0.882	0.807	0.807	0.804	0.823	0.714	0.751	0.754	0.783	0.684	0.729
40	0.880	0.880	0.806	0.806	0.805	0.824	0.715	0.751	0.755	0.784	0.685	0.729
50	0.881	0.881	0.808	0.808	0.804	0.821	0.714	0.756	0.754	0.781	0.684	0.726
60	0.882	0.882	0.806	0.806	0.804	0.824	0.714	0.756	0.754	0.784	0.684	0.728
70	0.883	0.883	0.808	0.808	0.805	0.824	0.715	0.755	0.755	0.784	0.685	0.730
80	0.885	0.885	0.809	0.809	0.803	0.824	0.713	0.755	0.753	0.784	0.683	0.729
90	0.882	0.882	0.809	0.809	0.804	0.825	0.714	0.754	0.754	0.785	0.684	0.720

tunnels) are considered in the TE strategy, MPR's approach is holistic given its link-state nature and offline TE approach, as it takes into account the entire network's topology (i.e. resources). Here, we compare the two methodologies in terms of both online and offline TE mechanisms. Due to the complexity and overhead associated with the MPLS implementation (see Section 2.5 and [2]), we consider the simulation scenario described in [21] (previously referred to as the GW anchored scenario). In this scenario, the number of *Ingress-Egress* pairs is smaller than that of section 4.5.2 thus reducing the effects of scalability and overhead issues affiliated with MPLS.

Reliability

MPR's offline TE approach as oulined in [17] was applied to build RPs for different meshings (Table 4.1) ahead of the traffic flow in the network. In the case of MPLS, Dijkstra-based K-path routing was applied to build the same number of paths as the MPR case to allow for the creation of L multiple paths for every *Ingress -Egress* pair, while ensuring one edge-disjoint path (or atleast a maximum number of edges being disjoint if not all) with a hop-count threshold [2]. In MPLS offline TE (network planning phase), LSPs are obtained based on a set of given metrics as detailed in [2] (namely hop-threshold and an edge-disjoint path) hence reducing the number of LSPs to as many as desired by the network planner with the aim of alleviating the scalability issues associated with LSP construction. Accordingly, we set the criteria such that the same number of LSPs as the RPs in the MPR case were obtained (i.e. equivalent to our configuration) $(L \equiv N)$.

As also indicated in Section 3.6.2, reliability is defined as the probability of the session for every *Ingress-Egress* pair (i.e. commodity) not being interrupted by any factors such as link failure [103]. Lower reliability can have a negative impact on service delivery and QoS performance [104]. If failure is associated with some probability p, with the assumption that failures are independent and equal for all the links, the probability of a path with h arcs being operational is given by $(1-p)^h$ [88]. In addition to the length of a path being a penalizing factor, the individual links would also be penalized if encompassed in more than one plane or overlap with more than one LSP path equivalently. The overall reliability per demand across a set of available independent routing planes was derived in equation (3.15).

It is straightforward to conclude that every individual path in one plane with a lower hop-count would have a higher reliability. It is also notable that with more diversity and fewer paths overlapping, reliability would increase correspondingly. Table 4.10 illustrates the reliability indicator for all the demands across the total available RPs/LSPs. The reliability in the case of the MPLS method is consistently lower compared to MPR (where the number of LSPs and RPs built are equivalent). This is mainly due to more links having been overused and hence further penalized throughout the constructed LSP paths in comparison with MPR (where the offline algorithm considers the whole topology and uses all the links (i.e. resources)). Consequently, it can be concluded that more meshing is possible in networks that favor MPR with minimal construction overhead of planes. The results obtained in Table 4.10 are based on a set of distinct probabilities of failure being randomly distributed among the links.

Table 4.10: Reliability

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_2
MPR	0.73	0.53	0.62	0.49
MPLS	0.51	0.47	0.41	0.45

Online Performance Comparison

In the case of the MPLS-based TE where pre-constructed static LSPs are used, traffic and resource optimization are achieved through online forwarding adaptation [2]. In the case of MPR and QMPR, the plane selection policy as described in Subsection 5.3.5, is applied to route traffic among the available RPs. Different metrics are analysed by being averaged over snapshots throughout the simulation time.

Table 4.11 illustrates the throughput for various strategies. With MPR, the availability of a diverse set of routes across the demand set facilitates the splitting of traffic over several diverse

Table 4.11: Throughput (Mb/s)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_1
OSPF	34	34	47.5	47.5
MPR	50.6	51.2	77	77.7
QMPR	49.5	49.7	70.8	71.1
MPLS	46.8	50	72.2	74.4

Table 4.12: Blocking Rate(%)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_1
OSPF	17.8	17.9	61.1	61.1
MPR	6.3	6.1	52.2	50.1
QMPR	9.4	8.3	54.1	53.9
MPLS	9.2	8.4	56.1	52.4

Table 4.13: Maximum Link Utilization (MLU)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_1
OSPF	0.816	0.816	0.932	0.932
MPR	0.79	0.78	0.92	0.911
QMPR	0.71	0.69	0.914	0.907
MPLS	0.808	0.808	0.924	0.921

Table 4.14: Delay (ms)

TE Method	T_1M_1	T_1M_2	T_2M_1	T_2M_1
OSPF	6	6	100	100
MPR	16.6	35.1	110.1	119.2
QMPR	14.7	16.6	109.8	118.9
MPLS	11.2	13.3	109.9	118.92

paths, leading to improved load balancing within the network. In MPLS, the smaller throughput as compared to MPR is a result of a lower diversity that causes a higher blocking of traffic. The higher blocking rate in the case of QMPR, which is due to the exertion of QoS criteria, leads to its slightly worse performance compared with MPR and MPLS in certain topologies. The existence of only one route for every demand in the case of the OSPF/InvCap method results in higher blocking and lower throughput. It can be also observed that throughput is generally higher in the case of different routing methods for the second set of topologies as compared with the first set which is smaller in terms of links and nodes. This is due to a relatively larger traffic volume in the second topology thanks to more traffic sources as explained earlier in Section 4.5.1.

As observed in Table 4.12, the blocking rate is lower in the case of MPR as compared with MPLS. This is because of a higher number of available paths with the required bandwidth thanks to the higher diversity. The blocking rate in the case of OSPF is the highest as there exist for much fewer available paths. In QMPR, the best RP (i.e. the best path) is selected for routing every incoming session towards its destination based on the QoS requirements and the state of the RP. This results in more sessions being blocked due to the lack of available qualified paths. Moreover, a higher blocking rate has occurred in the case of the second set of topologies ($T2My$) as compared to the first set ($T1My$) which is due to the different traffic distribution model as explained previously (i.e. Section 4.5.1).

As observed in Table 4.13, the Maximum Link Utilization (MLU) is lower in the case of MPR as compared to MPLS and OSPF. This is due to the availability of multiple diverse paths and the full utilization of resources (i.e links) in the network in the case of MPR. QMPR's application leads to generally lower MLU as traffic is engineered based on QoS requirements. This corresponds to less traffic flowing in the network due to the enforced QoS criteria causing deferrals. It can be also concluded that the network gets congested faster in the case of MPLS and OSPF as compared with the MPR methods. With the increase in meshing across the topologies, the general trend points to the reduction in MLU as a result of a higher number of available links in the network.

In the case of MPR and QMPR, as shortest-hop routes are not always used, higher delays are experienced by the sessions forwarded onto the RPs. Table 4.14 demonstrates the higher delay in the case of MPR and QMPR. The lower delay in the case of MPLS is due to shorter routes in terms of hops having been traversed. However, with the increase in the network meshing and number of nodes, it can be observed that the MPLS performance worsens. OSPF uses a single shortest route for every demand resulting in the lowest delay in comparison. It is important to note that more packets are delivered in the case of MPR and QMPR (where the entire network's routing resources are utilised) leading to a higher overall delay at the cost of a higher throughput and a smaller blocking rate. As mentioned in Section 4.5.2, there is a trade-off between delivering more traffic with multi-path routing over longer paths and increased average delay [100, 101]. Therefore, it can be concluded that multi-path routing would lead to seemingly higher delays as there is less session blocking. In other words, the delay minimization objective in multi-path routing surpasses that of static shortest path routing with less path diversity. This is because of more traffic being admitted with the gradual overflowing of network comparatively in the case of multi-path routing. Additionally, a generally higher delay is incurred in the second set of topologies as compared to the first set, which is due to the larger size of the network. It is important to note that the delay in access networks might be negligible as compared with the delay to and from the Internet. Moreover, as planes do not change for sessions once the first packet is admitted, there are no variations in packet delays in normal load situations and transport layers would not be disrupted.

4.6 Summary

In this chapter, IP TE-based MPR has been remodelled to suit the future all-IP access network structures by utilising the entire network's routing resources. The evolution of network architecture designs as reflected in the trend towards a flat-IP structure, along with the rise of

IP-based real-time applications call for a consistent routing paradigm. MPR augments the constrained shortest-path routing paradigm allowing the network to deploy path diversity by concurrently maintaining several independent logical topologies. The resultant diversity allows for network wide load balancing and is suited to various topological configurations. Being facilitated by multiple OSPF topology instances in networks that are controlled by offline and online algorithms, MPR achieves path diversity with minimal extra protocol overhead.

Moreover, heuristics have been applied for both offline and online TE solutions respectively, due to the NP-complete nature of finding suitable RPs in diverse practical topologies, and the use of multiple QoS metrics for realistic traffic types to be supported by network's routing. Two cases that are reflective of the evolution in the network architecture design have been investigated in terms of various metrics under fluctuating internal/external traffic distributions to emulate a comprehensive realistic set of traffic scenarios that facilitates a thorough performance evaluation. In addition to the demonstration of MPR-based methods' superiority over legacy OSPF/InvCap methods, it has been shown that the flat-IP based design concept (Case II) outperforms the hierarchical-based concept (Case I). Additionally, the surge in the internal traffic ratio has resulted in performance degradation under both network architecture design concepts but has generally improved with more meshing in the networks. It has been also shown that MPR outperforms MPLS in terms of reliability and online TE mechanism besides the MPR's ease of protocol deployment.

In the upcoming chapter, a traffic class, namely Tactile Internet, and the facilitation of routing the packets associated with this class will be considered in our study. Correspondingly, MPR will be extended to support this new traffic type which is associated with strict QoS characteristics. To this end, a reliable novel routing policy (i.e. Tactile Aware Policy (TAP)) will be introduced for the purpose of serving haptics communication effectively over all-IP access networks. A performance evaluation in terms of various measures will be presented that includes comparisons against some rival routing schemes.

5

A Novel Reliable Routing Scheme for Tactile-oriented Internet Traffic

5.1 Introduction

In the previous chapters, MPR's offline and online algorithms were extended to reflect the changing architecture of access networks while integrating various associated practical aspects in the investigation. All the presented simulation results verified MPR's performance potential and its superiority over its rival strategies in all-IP access networks. In this chapter, the Tactile Internet will be accommodated, which represents another practical application of MPR. To this end, a novel reliable MPR-based routing scheme is proposed in consideration of the specific Tactile Internet's characteristics and requirements.

Presently, the Internet supports voice and data communications in addition to multimedia services such as audio and video. Over the past few years, many scientists have envisioned an Internet generation that will not only provide voice and data communications but can also support haptics communication. Correspondingly, the Tactile Internet must enable haptics communication [77] as a major application and provide the medium for transporting such information. This new Internet dimension can be beneficial for the society by facilitating the development of new technologies and applications that will improve our standards of living. In this chapter, a novel traffic engineering policy that can satisfy the extremely strict requirements of the new traffic class associated with haptics communication is proposed. Our proposed policy is based on MPR that consolidates various aspects of an all-IP access infrastructures and enables network-wide path diversity as oulined in the preceding chapters. To this end, MPR has been remodeled and extended to facilitate haptics communication. Our simulation results demonstrate that our proposed policy outperforms intra-domain routing protocols namely OSPF and performs near-optimally. It will also become apparent that shortest-path solutions such as OSPF cannot be used in order to handle haptics communication in typical Internet network topologies. Finally, we formulate a binary optimization problem for the selection of the optimal routing plane in terms of the network effects such as delay, jitter and packet loss.

It is expected that Tactile Internet communication would be feasible in scoped and/or reasonable communication distances. This is due to the associated strict requirements being hard to administer over the ranges of Internet networks that can be traversed by the packets with different traffic flow requirements. Therefore, the current study is focused on scoped network(s) or single administrative domains (namely access networks) where a routing optimization policy can be enforced. This chapter presents simulations results pertaining to Tactile-oriented packet streams under different performance criteria.

5.1.1 MPR's Application in haptics Communication

MPR was initially proposed in [17]. A study has recently emerged containing the detailed analysis of MPR [20]. As stated previously, MPR is based on the MT-OSPF principle that unites various aspects in the all-IP network infrastructure. MPR aims to maximise path diversity in access network topologies (campus and metropolitan area networks) by applying a purely IP-based Traffic Engineering (TE) approach where multiple logical routing planes that represent instances of OSPF are built (see Section 3.4). Hence, the availability of multiple routing paths for each *source-destination* (i.e. *Ingress-Egress*) pair in the network is ensured. MPR was investigated and extended in Section 4 to include more diversity and cover various network routing scenarios, including all options for *Ingress-Egress* pairs and downlink/uplink traffic flows. MPR with extensions in routers' queues (i.e. resembling a coupling with DiffServ approaches) is an attractive routing solution for haptics communication in scoped access networks as it allows a network wide efficient differentiation of routing resources. MPR is already proven to achieve performance gains against MPLS and OSPF considering the overall network and a significant number of key performance criteria as presented in section 4.5.3 and [105]. Furthermore, the offline and online separation of algorithms in MPR allows for pre-planned and extremely responsive adaptations to various traffic requirements, making it a more adaptable and faster solution than conventional IntServ schemes and native SDN approaches that are seen as incurring route configuration delays that can prove to be intolerable in the case of Tactile Internet.

It is notable that a relevant Internet protocol called Efficient Transport Protocol (ETP) was proposed in [106]. ETP is a protocol focused on real-time applications and its main objective is to reduce Round-Trip Time (RTT) and Inter-Packet Gap (IPG). Therefore, ETP is optimized for interactive applications hence making it a candidate transport protocol for haptics communication. Nevertheless, ETP will not be considered in this study as it has not yet been deployed.

5.2 Novelty

The main contribution of this chapter is to design a reliable routing policy to accommodate haptics communication using delay, jitter and packet loss, alongside capacity, as combined path selection criteria. To the best of our knowledge, such a policy that is designed in order to handle Tactile packets subject to the strict and multiple limitations is absent in literature where most of the solutions for expedited routing (either best-effort or multi-path) reduce the objective to a convoluted cost or apply reductions to one or a few criteria that are chosen as being pertinent. As we are at the stage of validating the possibility of supporting Tactile traffic in scoped Internet networks with three specific criteria (i.e. delay, jitter and packet loss), keeping all three with equal bearing is considered a practical necessity (presuming bandwidth is available). Our policy is based on the application of MPR as a routing solution for access networks (i.e. Intra-domain routing in single administrative domains) which has been remodelled to allow for reliable communication for Tactile packets by allowing two types of queues to be installed in routers, for priority and non-priority traffic classes respectively. To this end, a new mathematical model has been proposed.

5.3 System Model

5.3.1 Conceptual Background

As stated in the preceding sections, a network is partitioned by MPR into several logical planes enabling routers to maintain multiple independent logical RPs. Each RP can overlap with another RP and share any sub portion of the network topology. Moreover, every RP represents an OSPF instance that is correlated with a particular link weight setting. The different OSPF instances converge to maximise path diversity and can be used to increase the reliability of the communication.

The communications' reliability is further enhanced by forwarding duplicate packets of the same nature (i.e. Tactile) on two of the best available RPs having been ranked in terms of cost. MPR is able to support up to 8 RPs by using the IPV4-header integrated Type of Service (ToS) field (as put forward by IETF in [95]), [1] therefore bearing no extra overhead on IP packets. It has been proven that a performance close to optimum in terms of link utilization can be achieved by using 3-5 RPs for similar cases of topologies [17] (see section 4.4.2 for more

[1] MPR is expected to be attractive in future Internet implementations using IPv6 suite, where additions of plane information bits in IP packet's header is more extensive

details).

5.3.2 Experimental Setup

The network in Figure 4.1 represents an Autonomous System (AS) which constitutes a metropolitan or campus access network with a single gateway towards the big Internet. All Aggregation Routers (ARs) and the Gateway (GW) can act as Ingress or Egress points for traffic in the network. Traffic can be to/from external Internet networks or internal between ARs. This reference fat-tree model is based on [23]. The network is comprised of 6 base stations acting as ARs. Nodes are considered to be interconnected by wired Ethernet links. Two $M/M/1$ queuing models are considered for every node, one for priority class packets and one for non-priority class packets. The priority class is dedicated to Tactile related traffic whereas the other traffic types would use the non-priority class. Link capacities are set depending on the level they belong to in our reference network following a uniform distribution. [360, 400], [200, 240], [140, 180] and [60, 100] are used respectively for the four different levels in the network studied as marked in Figure 4.1 (an example of the routing planes' breakdown can be observed in Figure 3.1).

5.3.3 Offline RP Construction

MPR's offline RP construction was discussed in detail in the preceding chapters (i.e Chapters 3 4). MPR's offline algorithm has been designed in order to improve path diversity and facilitate an improved load balancing. The potential benefits of path diversity in access networks was investigated and ratified in [32]. To this end, MPR's offline approach was initially put forward in [17] and it was shown in [21] that by increasing path diversity, the performance of the network can be improved significantly. This algorithm is of an offline nature as it does not require the real time state of the network in order to build the planes. Three principles are enforced in this algorithm which are listed below:

1. Each link must not be used in at least one RP.

2. In addition to *Ingress-Egress* router pairs in the network, between which a route is ensured in every RP, the network contains transit routers that only route traffic without generating or absorbing it.

3. Each link is used in at least one plane.

MPR's offline TE approach is applied to build the RPs ahead of the traffic flow into the network.

5.3.4 RP selection Optimization Problem

MPR's online packet routing renders the best possible path (i.e. RP for packets belonging to a session). It is assumed that the information on the status of network's link usage is known by the ingress points where the plane/path selection is performed. As the paths/planes overlap for all the *Ingress-Egress* pairs in the network, the online algorithm can be represented as an optimization problem of choosing the best possible path, subject to the cumulative use of network's routing resources.

A binary optimization problem for RP selection is introduced in the online TE. The main aim of this formulation is to select the appropriate RP (i.e. path) for each session based on the class that the session's packets belong to. For instance, if the packets belong to the priority class, the optimization problem finds the RP that is optimal in terms of delay, jitter and packet loss in line with the strict Tactile requirements. Herein, we consider three requirements to be of equal importance; therefore, they are normalized in the objective function. In the case in which the packets of the session belong to the non-priority class, the optimization problem finds a RP that solely satisfies the bandwidth constraint.

We denote the network effects by i ($i = 1$ represents delay, $i = 2$ represents jitter and $i = 3$ represents packet loss), the Tactile class constraint for session j by $\mathcal{L}_{i,j}$, the examined RP by n, the examined session by j, the network effects for RP n and session j by $l_{n,j,i}$, the required capacity for the priority class for the RP n by $c_{1,n}$, the required capacity for the non-priority class for the RP n by $c_{2,n}$ and the binary variable that enables us to select a specific RP n for a specific session j by $x_{n,j}$. C_n represents the bottleneck capacity of RP n.

$$
\begin{aligned}
\min \quad & \sum_{n\in\mathcal{N}}\sum_{j\in\mathcal{J}}\sum_{i=1}^{3} x_{n,j} e^{(o+\frac{l_{n,j,i}}{\mathcal{L}_i})} \\
\text{s.t.} \quad & \sum_{j\in\mathcal{J}} x_{n,j} c_{2,n} \leq \mathcal{C}_n, \forall n \in \mathcal{N} \qquad (a) \\
& \sum_{j\in\mathcal{J}} x_{n,j} c_{1,n} \leq \mathcal{C}_n, \forall n \in \mathcal{N} \qquad (b) \\
& \sum_{j\in\mathcal{J}} x_{n,j} l_{n,i,j} \leq \mathcal{L}_{i,j}, \forall n \in \mathcal{N} \ \ and \ \ \forall l \in \mathcal{L} \ \ (c) \\
& \sum_{j\in\mathcal{J}} x_{n,j} = 1, \forall n \in \mathcal{N} \qquad (d) \\
& x_{n,j} = 0 \ \ or \ \ 1, \forall n \in \mathcal{N} \ \ and \ \ \forall l \in \mathcal{L} \qquad (e)
\end{aligned}
\tag{5.1}
$$

In order to normalize the weight of each network effect we chose to use $e^{(o+\frac{l_{n,j}}{\mathcal{L}_i})}$ function. o is a constant that enables us to operate in different regions of the e^x function. Furthermore, as e is a monotonically increasing function it can only contribute additively by increasing the value of the objective function.

Constraints (a) and (b) ensure that every RP that will be selected has enough free resources in terms of capacity in order to support the new non-priority and priority sessions respectively. Constraint (c) stipulates that every RP that will be selected in order to serve a priority session has to satisfy the Tactile QoS requirements as shown in Table 5.1. Constraint (d) states that for every session, only one RP can be selected. Constraint (e) ensures that our optimization variable is a binary variable.

5.3.5 Tactile Aware Policy

The proposed Tactile aware TE algorithm is based on MPR's online TE policy which was initially proposed in [21]. MPR's approach has been remodelled to accommodate for the evolutionary Tactile Internet. To this end; two types of queues and a new plane selection policy have been introduced.

The Tactile Aware Policy (TAP) segregates the network into a hierarchy in the presence of traffic of both downlink and uplink nature. Every time a packet arrives at the *Ingress*, it is checked whether it belongs to a new session. If the packet that arrives at the *Ingress* does not belong to any existing sessions, then the *Ingress* node should apply the following principles. Firstly, the *Ingress* has to check if there is enough bandwidth in order to support the new session. In the case where, there exist enough free resources, the session will be admitted. However, if there are not enough available resources to be used, the packet will be dropped and the session will be rejected. When the session has been admitted, MPR's online algorithm will be used in order to route the packet. At this point, it is worth mentioning that when a route has been selected to route a packet, all the packets that belong to the same session will subsequently follow the same route to preserve the same transport conditions. In the following paragraphs, TAP's functionalities are described in detail.

Firstly, when a Tactile packet arrives at the *Ingress*, a duplicate is generated. The initial packet will be routed by using the best path in terms of delay and the duplicate packet will be routed on the second best path in terms of delay. The main idea behind the generation of the duplicate packet is to increase the communication's reliability which is vital in case of Tactile traffic. The duplicate packet generation helps in reducing the packet loss that is one of the main constrains that needs to be dealt with. When the initial packet has been dropped, there is a possibility that it can be restored by the duplicate. Based on TAP, the packet that arrives first at the *Engress* is considered to be valid. In case of both packets having been delivered successfully, the one that has arrived second will be dropped.

Another major constraint of the Tactile Internet is that the round trip time must not exceed the threshold of $1ms$. In order to achieve this, the packets are categorized into two classes. The first class (i.e. priority class) represents the Tactile packets and the second class represents all the other types of packets (i.e., VoIP, Web etc.). To this end; it is assumed that each router has two queues. One for the priority class packets and one for the packets that belong to the other classes. The router's scheduler will try to serve the packets from the first queue. When the priority queue is empty or the non-priority queue has been used for a long period, it will start serving packets from the non priority queue. However, in the case where a priority packet arrives at an empty priority queue while the scheduler is serving a non-priority packet, the priority packet has to wait until the scheduler pushes the non-priority packet to the link. By following this strategy, the queueing delay will be reduced significantly leading to the overall reduction of delay. Finally, priority packets are inserted prior to the non-priority ones in case the queue is full of non-priority and priority packets arriving at the queue. This is due to the objective of avoiding starvation for the non-priority class packets while providing high priority to the priority class packets. The TAP policy is summarized in Algorithm 3.

In the network, a set of users is defined as $\mathcal{B} = \{b : b = 1, ..., B\}$. $\mathcal{T} = \{t : t = 1, ..., T\}$ indicates the set of traffic types. $\mathcal{Q} = \{q : q = 1, ..., Q\}$ represents the set of sessions. c_q^t is defined as the QoS constraint of session q associated with traffic type t. $|\Pi^{b,d}|$ indicates the traffic rate associated with user b and demand d. We denote the available bottleneck bandwidth for path p_n^d by $b(p_n^d)$.

Algorithm 3 Tactile Aware Policy

procedure E-POLICY-PS($P_n^d, \tau, \kappa, \mathcal{N}, V$)
  packet arrives at the Ingress r $\in$ V destined to the Egress g $\in$ V
  if packet does not belong to an existing session (i.e. new session) **then**
    Perform lookup and check traffic class t $\in \tau$
    Obtain QoS requirements c_k^t for traffic class t
    if $|\pi^{b,d}| \leq b(p_n^d)$, for at least one $n \in \mathcal{N}$ **then**
      Session is admitted
      if the arrived packet $\in$ tactile traffic class **then**
        Add packet to the priority class.
        Generate a duplicate of the concerning packet
        Add duplicate packet to the priority class
        Select RP x_1 with the lowest cost $f(x)$ and x_2 with the second lowest cost $f(x)$ for the session associated with user u given: $f(x_1) \leq f(x_2) \leq ... \leq f(N - \bar{X})$.
        Route the original packet by using x_1 and the duplicate through x_2.
      else
        Add packet to the non-priority class.
        Select RP x_i in a random manner
        Route the packet through x_i.
      end if
    else
      Reject Session
    end if
  else
    Add packet to the same class as the previous ones that are part of the same session
    Route packet by using the already assigned RP to the previous packets that belong to the same session
    if arrived packet $\in$ tactile traffic class **then**
      Generate a duplicate of the concerning packet
      Route the duplicate by using the already assigned RP to the previous duplicates that belong to the same session
    end if
  end if
end procedure

Table 5.1: Traffic types[1] and associated QoS requirements.

Traffic Class	Data Rate	Mean Duration	QoS requirements		
			Latency	Jitter	Packet loss
Class 0	Low (≈ 150 Kbps)	180 sec	1 ms	20 μs	0.00001 %
Class 1	Low (≈ 150 Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium (≈ 250 Kbps)	300 sec	4-5 s	*none*	5 %
Class 3	Low (≈ 128 Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High (≈ 500 Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low (≈ 100 Kbps)	90 sec	*no specific requirement*		

[1] Applications examples; Class 0 : haptics, Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

5.4 Performance Evaluation

In this section, the results that were obtained for the two proposed topologies using C++ and packet-level NS2 simulations interfaced with Matlab are presented and analysed. RPs are created through the offline algorithm before NS2 is applied for traffic injection. Subsequently, incoming sessions that belong to different traffic classes (as represented in Table 5.1) are generated randomly. The results demonstrated correspond to Haptics traffic performance. It is notable that the traffic type sessions are uniformly distributed. The simulations last for 12 seconds in real time where the results at a sampling rate of 10 times per second are recorded. Traffic is injected into the network in an increasing manner by reducing the inter-arrival times of the generated sessions. In the case of the T_1 topology, the overall traffic volume in the network increases up to approximately 330 Mb/s, whereas in the case of the T_2 topology the traffic volume goes up to 480 Mb/s. Full network utilisation and significant congestion occur between the 11s and 12s intervals. The results associated with the second topology are presented in Appendix B. Since the topologies correspond to campus or metropolitan networks, the propagation delay of each link is set to 0.007ms (assuming an upper bound for the length of the cable of 20km). Transmission and processing delays are added as part of the NS2 router and queuing model. When a new session arrives at the Ingress, it will check if there exists enough available bandwidth on the set of RPs in order to admit the session regardless of the method used (OSPF, TAP). The TAP online TE mechanism, as described in Subsection 5.3.5, is applied to route the traffic. MPR and the generation of the duplicate packets have been implemented using NS2 whereas the priority queueing model has been developed using C++. Our proposed policy is compared with OSPF and an optimal case of TAP. First of all, an optimal bound for TAP was derived by allowing only packets of Tactile nature to flow through the network. Subsequently, as mentioned above, different types of traffic (i.e. including Tactile) were allowed to flow through the topologies in order to evaluate the performance of the proposed algorithm under a realistic scenario. The results that are represented in terms of the most critical metrics (i.e. delay, jitter, throughput and packet loss) pertain to haptics traffic performance.

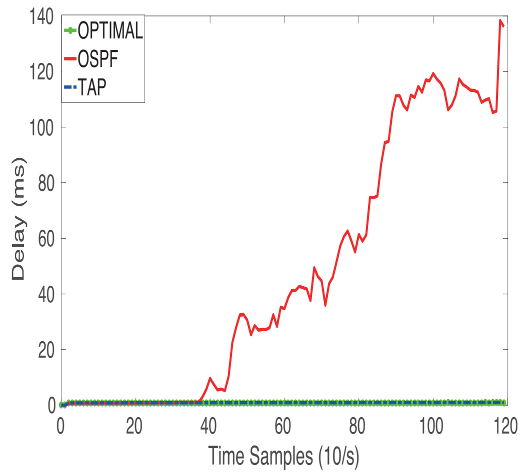
Topology	OSPF	Optimal	TAP
T_1M_1	47.6274	0.818168	0.889203
T_1M_2	47.6274	0.80454	0.875463

Table 5.2: Average delay (*ms*)

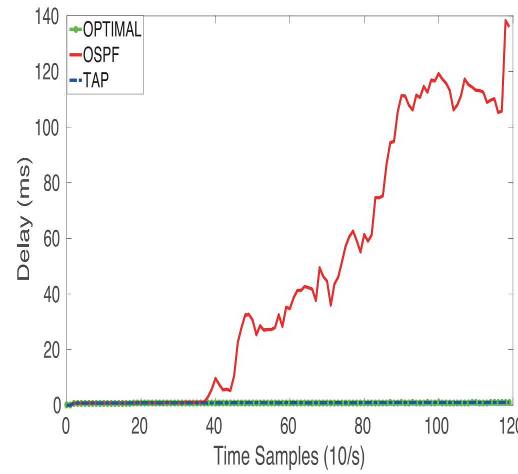
Delay (ms)

We use Table 5.2 to present our data because the difference between the optimal case and TAP is not possible to be visualised with graphs. As it can be observed from Table 5.2, the T_1M_2 topology has a slightly better performance in terms of the expected delay as T_1M_2 has more links compared to T_1M_1. Consequently, the traffic can be distributed better over the network due to the existence of more RPs; therefore, the mean delay will be reduced as the queues are less cramped and longer routes do not affect the delay. As expected, TAP performs to some extent worse than the optimal. The main reason behind this difference is the fact that a non-priority packet being served while a priority packet arrives at the empty priority queue. In this case, extra queuing delay will be added to the priority packets leading to an increase in the expected delay. In general, TAP performs extremely well in terms of delay even when the traffic congestion in the network is very high. To be more specific, the delay would never exceed the threshold of 1 ms. On the other hand, as illustrated in Figure 5.1, plain vanilla of OSPF cannot support haptics communication due to the high values of delay incurring cyber sickness to Tactile applications. The main reason behind the big difference between OSPF and TAP is that OSPF does not facilitate any priority for the packets that belong to the Tactile class in addition to the lack of diversity. Consequently, the queueing delay will be extremely high.

[1]It is important to note that at-least two RPs in case of the Tactile traffic class and one for the other traffic types were present throughout the simulation time up to the congestion point as enforced by the algorithm



(a)

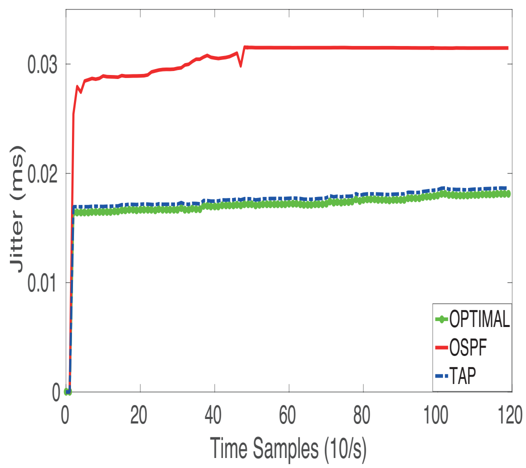


(b)

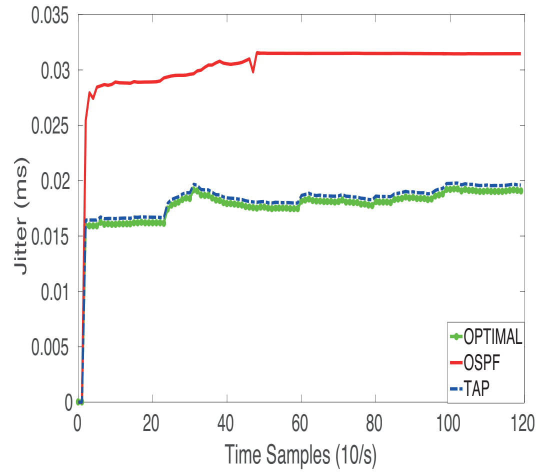
Figure 5.1: Delay (ms) for our investigated topologies (a) T_1M_1 (b) T_1M_2

Jitter (ms)

Jitter is a crucial QoS factor in the assessment of network performance. In the case of Tactile applications, jitter should not exceed the threshold of $20\mu s$. In Figure B.2, the variation in latency for a randomly chosen *Ingress-Egress* pair is measured. The same *Ingress-Egress* pair was used for both of our proposed topologies. As observed in Figure B.2, the overall trend shows an increase in jitter. This is due to the larger variations of packet delay resulting from the increasing congestion in the network. Furthermore, both TAP and the optimal case perform extremely well (i.e. they never exceed the threshold of $20\mu s$). Meanwhile, OSPF's jitter values are around $30\mu s$. To this end, OSPF's performance is reflective of its inadequacy in supporting Tactile applications. Finally, TAP performs slightly worse than the optimal scenario due to two main reasons. Firstly, the duplicate packet uses a different path compared to the original packet with a generally higher delay in the case of the former. Consequently, when the original packet has been dropped, the duplicate packet with a higher delay is considered leading to a higher variation of flows' delay. Secondly, in the optimal case, only packets belonging to Tactile class are allowed to flow through the network. To be more specific, there are no other packets belonging to other traffic classes that would add extra queueing overhead leading to higher delay variations. Therefore, the optimal case performs slightly better than TAP in terms of jitter.



(a)



(b)

Figure 5.2: Jitter (ms) for our investigated topologies (a) T_1M_1 (b) T_1M_2

Packet Loss Rate

In the case of the Optimal scenario where only Tactile packets flow through the network, the traffic level is not so high to cause a queue overflow, hence leading to no packet loss as observed in Figure 5.4. The loss rate in the case of TAP is the same as optimal. This happens due to two main reasons. Firstly, each router has two queues; one for priority packets and the other for the non-priority packets. This leads to non-priority packets not adding extra queuing delay to priority packets which would otherwise cause packet drop due to buffer overflow. Secondly, even in the case where a priority packet has been dropped, it will be restored using a duplicate packet. Namely, for the T_1M_1 topology, 13 packets are restored by using the second flow and 8 for T_1M_2. More packets that belong to the first flow have been dropped in case of T_1M_1 as compared with T_1M_2 as T_1M_1 topology has a lower meshing relative to T_1M_2; Therefore, fewer RPs are available also as indicated in [21]. Conversely, when the congestion throughout the network is high, OSPF performs poorly making it a non viable candidate routing protocol for Tactile packets. The overall achieved loss rate of TAP for Tactile traffic was initially $5.0839\,*$

10^{-5} for T1M1 and $3.123 * 10^{-5}$ for T1M2. By duplicating sessions for Tactile traffic, the loss rate for both topologies was completely eliminated.

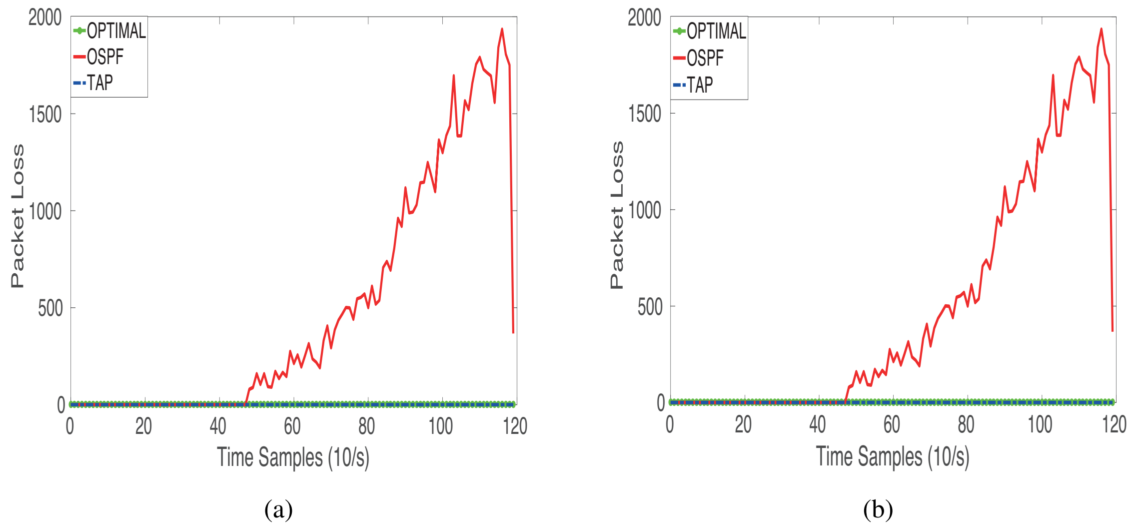


Figure 5.3: Packet Loss for our investigated topologies (a) T_1M_1 (b) T_1M_2

Throughput (packets/s)

Figure 5.4 illustrates the achieved network's throughput under varying traffic classes with an increasing traffic rate injected through the network (i.e. totalling 750MB over the course of 12 seconds). As observed, the achieved throughput of TAP is similar with that of the optimal cases. This can be explained by the fact that TAP achieved the same packet loss rate as the optimal case. Meanwhile, the OSPF protocol performs poorly when the level of congestion throughout the network is high.

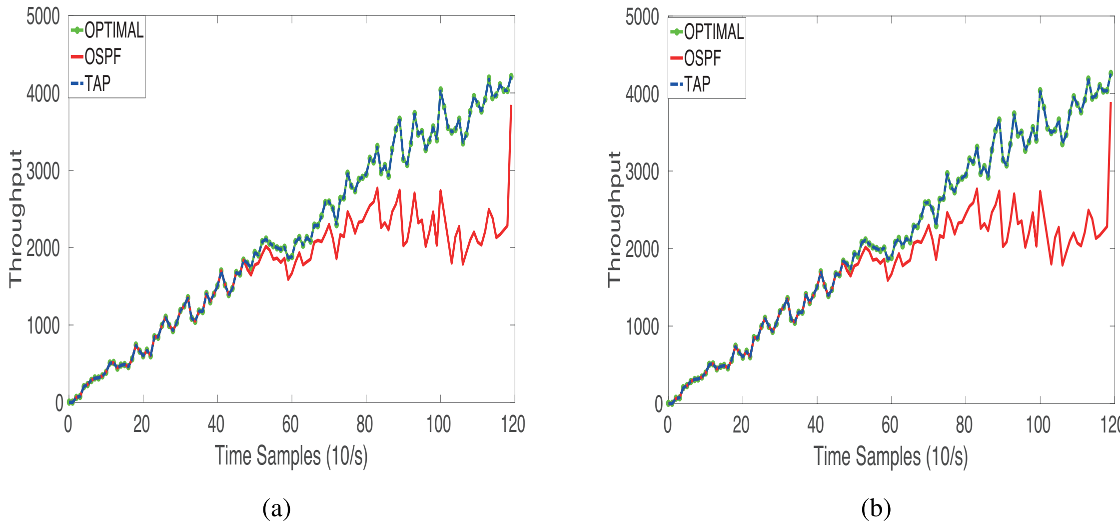


Figure 5.4: Throughput (Packets/s) for our investigated topologies (a) T_1M_1 (b) T_1M_2

5.5 Summary

In this chapter, a reliable novel routing policy has been proposed in order to serve haptics communication effectively over all-IP access networks. Two different access network topologies of different meshings have been investigated under a realistic traffic scenario with a varying range of traffic classes. Our proposed policy aims to ensure a high communications reliability for Tactile packets through duplication along with the facilitation of a priority queuing model. It has been shown that our policy performs extremely well for different levels of congestion (outperforming OSPF and performing not far from the optimum) in terms of various metrics (namely delay, loss rate, throughput and delay). Moreover, as TAP is based on MPR that is a purely IP-based traffic engineering approach, it would render negligible communication overhead in the network.

In the next chapter, conclusions on this thesis will be laid out followed by elaborations on possible extensions of this research as future work.

6

Conclusions and Proposed Future Work

6.1 Conclusions

The architectural evolution of convergent all-IP access networks as reflected in the trends towards a flat-IP structure, along with the rise of IP-based real-time applications and new traffic types, call for consistent transformations in the routing optimization approaches. To this end, MPR that consolidates various aspects in all-IP infrastructure and offers diversity facilitated by the network maintaining several independent logical topologies, has been extended to become adaptive in line with some increasingly relevant architectures and practical applications.

MPR augments the constrained shortest-path routing paradigm allowing the network to deploy path diversity. Being facilitated by multiple OSPF topology instances in networks that are controlled by offline and online algorithms, MPR achieves path diversity with minimal extra protocol overhead. Correspondingly, the resultant diversity allows for network wide load balancing and is suited to various topological configurations as verified through investigations. Heuristics have been applied for both offline and online TE solutions respectively, due to the NP-complete nature of finding suitable RPs in diverse practical topologies, and use of multiple QoS metrics for realistic traffic types to be supported by the network's routing.

IP TE-based MPR has been remodelled in terms of both its offline and online approaches to suit the future all-IP access network structures facilitated through the use of the entire network's routing resources. MPR's offline algorithm has been extended with a hop-constraint in order to select a set of RPs, resulting in an optimally configured network while accommodating a flat-IP architecture with the expected direct IP connectivity. Moreover, QoP, which gauges the quality of the RPs in terms ofvarious metrics in the offline mode, has been introduced. QoP can provide a qualitative overview of the candidate plane-sets in the offline mode. It was shown that with the hop-constraint approach, the number of RPs would be kept to the desirable level despite of having a higher number of sources and destinations.

Furthermore, two cases that are reflective of the evolution of the access network architecture design have been studied in terms of various metrics under fluctuating internal/external traffic distributions to emulate a comprehensive realistic traffic scenario that facilitates a comprehensive performance evaluation. In addition to the verification of MPR-based methods' superiority over legacy OSPF/InvCap methods, it has been shown that the flat-IP based design concept (Case II) outperforms the hierarchical-based concept (Case I). In addition, the rise in the internal traffic ratio has rendered performance degradation under both network architecture design concepts but has generally improved in line with increased meshing in the networks. It has also been demonstrated that MPR outperforms MPLS in terms of reliability and the online TE mechanism besides MPR's ease of protocol deployment.

MPR has also been extended to accommodate the Tactile Internet. To this end, a reliable novel routing policy has been proposed in order to serve haptics communication effectively over all-IP access networks. A realistic traffic scenario with a varying range of different traffic classes in the presence of Tactile packets has been considered. The proposed policy aims to ensure high communications reliability for Tactile packets through duplication along with the facilitation of a priority queuing model. It has been shown that our policy performs extremely well for different levels of congestion (outperforming OSPF and performing not far from the optimum) in terms of the various metrics studied. Moreover, as TAP is based on MPR that is a purely IP traffic engineering approach, it would render negligible additional communication overhead in the network.

There are remaining challenges that need to be investigated in order to facilitate MPR's adaptation in future access networks, further optimize its performance and present it as a complete practical solution. Correspondingly, the following section identifies other possible extensions and adaptations to this end.

6.2 Future Work

Like any other technique during its first years of development, MPR and its practical extensions introduced in this thesis still have a lot of room for improvement before it can become practically applicable in evolutionary all-IP access networks.

Polynomial time approximation can be adopted to identify and hence help improve MPR's performance in terms of time complexity in case of multiple QoS constraints (i.e. two or more). MPR integrates several QoS constraints in its approach in consideration of the increasing QoS criteria associated with increasingly variant traffic classes. To this end, a time complexity rivaling that of the best-known algorithm designed for this special case [107] will be investigated for MPR's QoS-aware approach.

Considering the trend towards heterogeneous architectures and the associated rising traffic volume, MPR's application with integrated diversity under a heterogeneous environment seems increasingly relevant. Moreover, in order to enable a generally applicable approach in future access network structures, it is essential for MPR's application in networks of a random nature (random graphs) to be studied. MPR's applicability and performance superiority's verification in case of random networks can further justify MPR as a practical routing optimization approach in future access networks.

A new optimization framework and hence a new RP construction method for the offline algorithm that takes into consideration the capacity and correlations between the candidate planes (i.e. a graph similarity metric) is being considered. The objective is to utilize the path with the highest capacity between every source-destination pair when formulating each plane while taking into consideration graph similarity. This approach can be extended to obtain a set of RPs and identify how close to optimum can be acheived given a flexible number of planes for a given topology when tested in an online scenario.

Weight re-setting and hence path re-configuration at different intervals based on residual capacity can also be applied through the newly developed RP construction method. SDN can be used in eliminating the overhead associated with path re-configurations. Under the new scenario, MPR can be compared against MPLS and ECMP in terms of performance and overhead. A new cost function that quantifies the cost of these approaches in terms of overhead, reconfiguration time and time complexity in addition to the consideration of bottleneck bandwidth and QoS metrics can also be developed. Such a cost function can provide a comprehensive comparative indication of the performance of these rival solutions in access networks.

In the case of Tactile applications, there is potential for more traffic variations to be investigated followed by the application of feedback and integration with extended traffic models for haptics. In addition, other intelligent and selective packet distribution and prioritization strategies along with various queuing models could also be investigated. The authors in [108] argue that there could be huge economic costs associated with QoS metrics namely jitter and delay not being met in consideration of rising variant traffic types. Correspondingly, a cost function can be developed that takes into consideration the economic benefits of serving Tactile packets efficiently in the presence of other traffic types. The varying percentage of potential Tactile traffic in a given network should also be considered in conjunction.

Appendices

Appendix A

Surrogate MPR's Online Traffic Engineering Optimization Approach

In the network; a set of users is defined as $\mathcal{B} = \{b : b = 1, \ldots, B\}$. $\mathcal{T} = \{t : t = 1, \ldots, T\}$ indicates the set of traffic types. $\mathcal{Q} = \{q : q = 1, \ldots, Q\}$ represents the set of sessions whereas m_q signifies the additive QoS metrics associated with every session q. c_q^t is defined as the QoS constraint of session q associated with traffic type t. $\Pi^{b,d}$ indicates the traffic rate associated with user b and demand d. We formulate MPR's online TE optimization based on [101] where only a special case for delay-sensitive traffic was considered and it was assumed that there exists access to shortest paths with flexible splitting of traffic over those paths with no specific supporting protocol. Our MPR-based formulation takes into account the existence of different types of traffic in the network whereas access to multiple paths is facilitated through the offline RP construction TE approach. MPR's online TE optimization objective is to minimize the associated cost depending on the path residual capacity and traffic type's associated QoS requirements for every session while also aiming to minimize the total traffic rate on every available path facilitated by the distribution of traffic among multiple paths (RPs). It is also ensured that the capacity constraint of every link is met. MPR's online TE optimization (i.e.

RP selection policy) is presented below:

$$
\begin{aligned}
\min \quad & \sum_{d\in\mathcal{D}}\sum_{n\in\mathcal{N}} Y^d_{P^d_n} \sum_{uv\in P^d_n} R^d_{uvP^d_n}\left((\frac{m_q(uv)}{c^t_q})^{\gamma_q} + (\frac{C_{uv}}{\widetilde{C}_{uv} - ||\Pi^{b,d}_{uv,n}||_0}) \right) \\
\text{s.t.} \quad & L_{uv} \le C_{uv}, \left(L_{uv} = \sum_{d\in\mathcal{D}}\sum_{n\in\mathcal{N}}\sum_{b\in\mathcal{B}} ||\Pi^{b,d}_{uv,n}||_0 \right) \\
& \sum_{n\in\mathcal{N}} Y^d_{P^d_n} = X^d \\
& Y^d_{P^d_n} \ge 0 \\
& m_q(P^d_n) \equiv \sum_{uv\in P^d_n} R^d_{uvP^d_n}.m_q(uv) \le c^t_q \\
& \forall d\in\mathcal{D}, \forall b\in\mathcal{B}, \forall n\in\mathcal{N}, \forall q\in\mathcal{Q}, \forall(uv)\in E, \gamma_q\in[0,1]
\end{aligned}
\tag{A.1}
$$

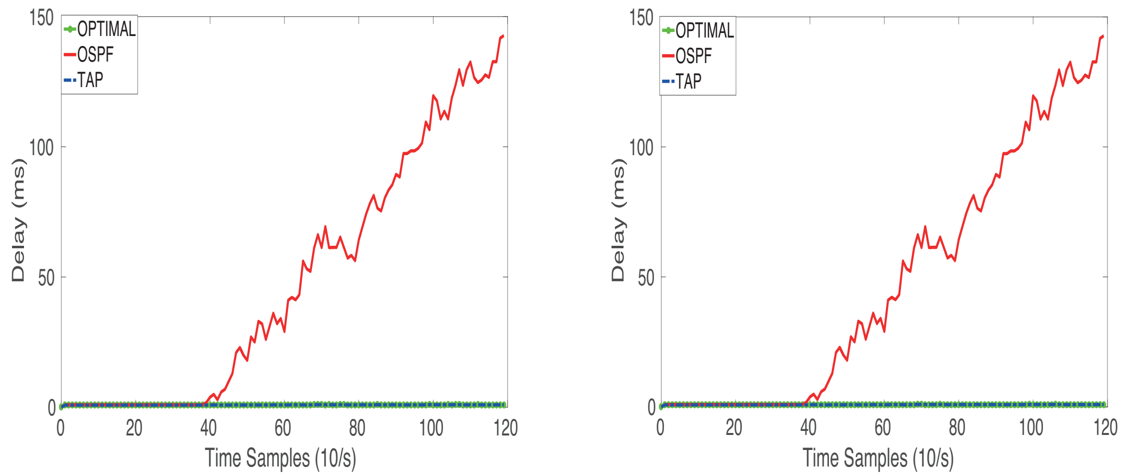
$Y^d_{P^d_n}$ represents the traffic rate on path P^d_n associated with demand d and RP n. X^d is indicative of the total traffic rate for demand d. $R^d_{uvP^d_n}$ is the routing matrix associated with link uv on path P^d_n (equation 1). $\widetilde{C}_{uv}$ signifies the residual capacity on link uv with link capacity C_{uv}. $||\Pi^{b,d}_{uv,n}||_0$ is indicative of the non-zero non-negative entries of $\Pi^{b,d}$ associated with plane n and link uv. The load on link uv is signified by L_{uv}. γ_q variables allow to give more priority to the concerning QoS parameters. RP selection policy is applied by MPR which is implemented through the sources (i.e. GW and ARs). In case of MPR, the available bandwidth on the RPs is initially determined and in case of the availability of more than one RP in terms of bandwidth requirements, the one with the highest bandwidth is selected. In case of QoS-MPR (QMPR), the qualified RPs in terms of bandwidth are selected taking into consideration packet's classification as determined based on its associated Service Level Requirement (SLR). Consequently, RPs that do not meet the requisite benchmarks associated with the concerning traffic class are eliminated with the most suitable RP in terms of our objective function being picked.

Appendix B

Additional Results for Tactile Internet in the case of the Second Network Topology (T_2M_1 & T_2M_2)

B.0.1 Delay (ms)

As it can be observed from Figure B.1 for the proposed T2 topologies, the same quality characteristics as in Figure 5.1 are rendered. The overall expected delay has increased approximately by an order of magnitude of 0.1 ms for both TAP and the optimal case. The reason behind this increase of the expected delay is one additional level of hierarchy having been added in case of the T2 topologies. Therefore, the packets would have to travel for at least one additional hop leading to extra queuing, nodal and processing delay. Furthermore, extra propagation and transmitting time will increase the expected delay even further. Generally, it can be seen that our proposed policy performs very well. Moreover, just in a few cases where the congestion level of the network is high, the threshold of 1ms is approximately touched. It is clear that OSPF performs poorly and cannot support haptics communication. Correspondingly, when the congestion level in our proposed topologies is high, the expected delay is much higher than the threshold of 1ms. Consequently, the user will not be able to control the virtual objects and will face cyber sickness.



(a) (b)

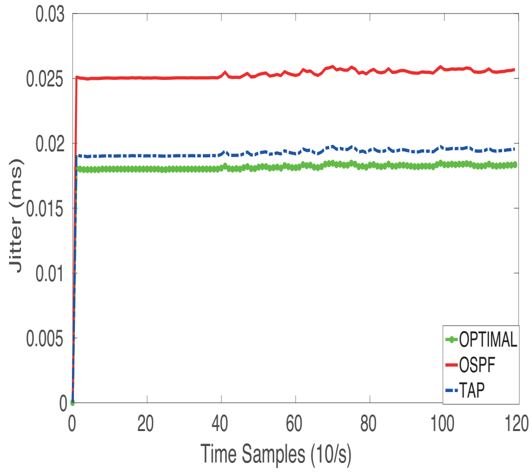
Figure B.1: Delay (ms) for our investigated topologies (a) T_2M_1 (b) T_2M_2

B.0.2 Jitter (ms)

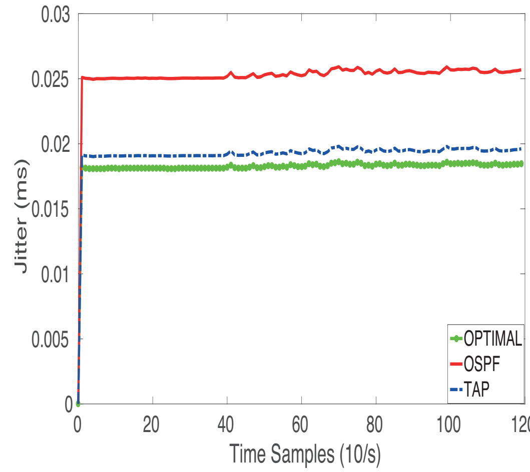
It can be observed that TAP operates below the threshold of 20µs; therefore, the strict jitter constraint has not been violated. As observable, TAP's jitter for T2 is slightly higher as compared with the T1 topologies. This can be justified by the addition of one more level of hierarchy. Namely, the addition of one more hop leads to extra queening that renders higher variations of the packet delay in the network. On the other hand, OSPF's jitter values are close to 25µs. Consequently, OSFP is unsuitable to route haptic communication over an autonomous system such as a metropolitan or campus access network.

B.0.3 Packet Loss Rate

Figure B.3 illustrates the packet loss for the three different examined routing policies. The packet loss in case of TAP is the same as the Optimal case. This can be justified by the fact that the second flow facilitates the restoration of the dropped packets. Furthermore, it is notable that each router has two different queues. One for the priority packets and one for the non-priority



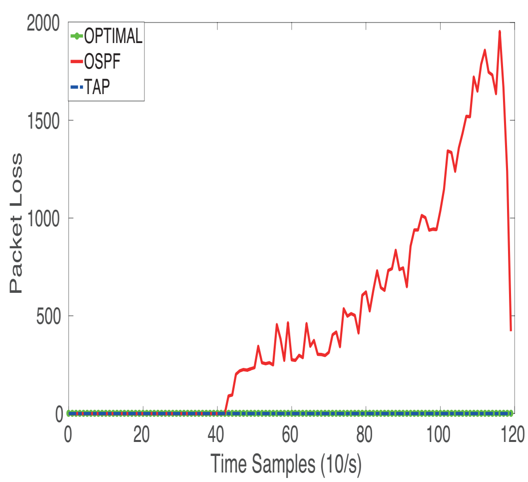
(a)



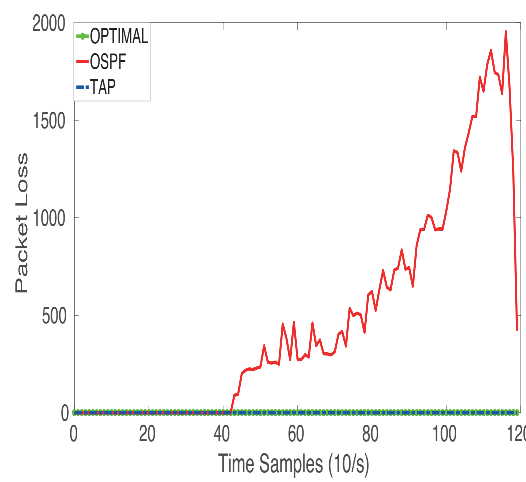
(b)

Figure B.2: Jitter (ms) for our investigated topologies (a) T_2M_1 (b) T_2M_2

packets; therefore, the non-priority packets cannot cause an overflow to the priority queue. On the other hand, the plain vanilla of OSPF use a single queue that handle all the packets the same way. Consequently, tactile packets are not shielded and have the same probability to be dropped as the other type of packets. Finally, OSPF does not use any mechanism to restore the packets that have been dropped. Therefore, OSPF is an inappropriate routing protocol for haptics communication.



(a)

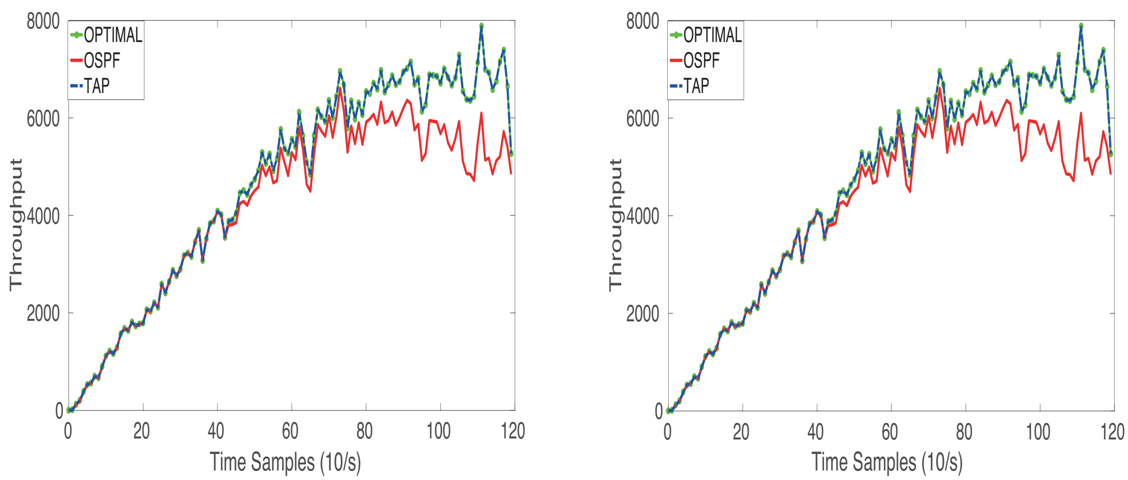


(b)

Figure B.3: Packet loss for our investigated topologies (a) T_2M_1 (b) T_2M_2

B.0.4 Throughput (packets/s)

As observed in Figure B.4, TAP and the optimal case achieve the same throughput. As the time passes, the level of congestion in the network topologies rises through the injection of more traffic hence having an adverse impact on the throughput. Overall, in both cases, 266.74 Mb was successfully delivered. Conversely, OSPF achieves a lower overall throughput. Namely, 240Mb has been delivered over a period time of 12s. The main reason behind the worse performance of OSPF is network's congestion leading to packets being dropped that corresponds to smaller data delivery.



(a) (b)

Figure B.4: Throughput (packets/s) for our investigated topologies (a) T_2M_1 (b) T_2M_2

Bibliography

[1] "http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html," in *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021*.

[2] N. Wang, K. Ho, G. Pavlou, and M. Howarth, "An overview of routing optimization for internet traffic engineering," *Communications Surveys Tutorials, IEEE*, vol. 10, pp. 36–56, Jan. 2008.

[3] R. Hancock, H. Aghvami, M. Kojo, and M. Liljeberg, "The architecture of the brain network layer," *IST Mobile Communications Summit*, 2000.

[4] A. Mihailovic, M. West, R. Hancock, P. Eardley, and T. Suihko, "Experience of the BRAIN and MIND projects in the development of IP mobility solutions," *IETF*, 2002.

[5] J. Fabini, P. Reichl, and A. Poropatich, "A generic approach to access network modeling for next generation network applications," in *Fourth International Conference on Networking and Services (icns 2008)*, pp. 254–260, March 2008.

[6] J. Fabini, P. Reichl, C. Egger, M. Happenhofer, M. Hirschbichler, and L. Wallentin, "Generic access network emulation for NGN testbeds," in *Proceedings of the 4th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities*, TridentCom '08, (ICST, Brussels, Belgium, Belgium), pp. 43:1–43:10, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008.

[7] O. Tipmongkolsilp, S. Zaghloul, and A. Jukan, “The evolution of cellular backhaul technologies: Current issues and future trends,” *IEEE Communications Surveys Tutorials*, vol. 13, pp. 97–113, First 2011.

[8] H. Raza, “A brief survey of radio access network backhaul evolution: part i,” *IEEE Communications Magazine*, vol. 49, pp. 164–171, June 2011.

[9] H. Raza, “A brief survey of radio access network backhaul evolution: part ii,” *Communications Magazine, IEEE*, vol. 51, pp. 170–177, May 2013.

[10] E. Rosen, A. Viswanathan, and R. Callon, “Multiprotocol label switching architecture,” *IETF*, January 2001.

[11] J. Moy, “Ospf version 2,” *IETF*, April 1998.

[12] C. Hopps, “Analysis of an equal-cost multi-path algorithm,” *IETF*, November 2000.

[13] A. Feldmann, A. Greenberg, C. Lund, N. Reingold, and J. Rexford, “Netscope: traffic engineering for IP networks,” *IEEE Network*, vol. 14, pp. 11–19, March 2000.

[14] B. Fortz and M. T. At, “Increasing internet capacity using local search,” *Computational Optimization and Applications*, vol. 29, pp. 13–48, 2004.

[15] L. Dean H., O. Ariel, and D. Raz, “How good can IP routing be?,” 2001.

[16] M. Maier, M. Chowdhury, B. P. Rimal, and D. P. Van, “The tactile internet: vision, recent progress, and open challenges,” *IEEE Communications Magazine*, vol. 54, pp. 138–145, May 2016.

[17] A. Jaron, A. Mihailovic, and A. Aghvami, “Introducing multi-plane routing for next-generation all-IP wireless access networks,” in *IEEE International Conference on Communications*, pp. 2856–2860, Jun 2012.

[18] N. Wang, K.-H. Ho, and G. Pavlou, “Adaptive multi-topology IGP based traffic engineering with near-optimal network performance,” in *Proceedings of the 7th International IFIP-TC6 Networking Conference on AdHoc and Sensor Networks, Wireless Networks, Next Generation Internet*, NETWORKING’08, (Berlin, Heidelberg), pp. 654–666, Springer-Verlag, 2008.

[19] M. Farhoudi, A. Jaron, A. Mihailovic, and H. Aghvami, “A new approach for routing plane construction in future multi-plane routing based wireless IP access networks,” in *IEEE Wireless and Networking Conference*, Apr 2016.

[20] M. Farhoudi, B. Abrishamchi, A. Mihailovic, and H. Aghvami, “A practical multi-plane routing-based traffic engineering scheme in evolutionary convergent all-IP access networks,” in *23rd International Conference on Telecommunications*, May 2016.

[21] A. Jaron, A. Mihailovic, and A. Aghvami, “Qos-aware multi-plane routing method for OSPF-based IP access networks,” *Computer Networks*, vol. 99, pp. 1 – 14, 2016.

[22] H.-H. Yen and F. Y.-S. Lin, “Near-optimal tree-based access network design,” *Computer Communications*, vol. 28, no. 2, pp. 236 – 245, 2005.

[23] D. Amzallag, J. Naor, and D. Raz, “Algorithmic aspects of access networks design in B3G/4G cellular networks,” in *IEEE 26th International Conference on Computer Communications*, pp. 991–999, May 2007.

[24] “https://5g-ppp.eu/wp-content/uploads/2014/02/5g-ppp-5g-architecture-wp-july-2016.pdf,” in *5G PPP Architecture Working Group*, Jul 2016.

[25] M. Bauer, A. Dekorsy, P. Schefczik, and M. Soellner, “IP-driven access-independent resource management in converged access networks,” *Bell Labs Technical Journal*, vol. 12, pp. 37–61, Summer 2007.

[26] B. A. Bjerke, “Lte-advanced and the evolution of lte deployments,” *IEEE Wireless Communications*, vol. 18, pp. 4–5, October 2011.

[27] "3GPP TS 36.300 - Evolved Universal Terrestrial Radio Access (EUTRA) and Evolved Universal Terrestrial Radio Access (E-UTRAN); overall description; stage 2," *3GPP Technical Specification Group Radio Access Network*, vol. v8.3.0, Jan. 2008.

[28] P. Bertin, S. Bonjour, and J. M. Bonnin, "A distributed dynamic mobility management scheme designed for flat ip architectures," in *2008 New Technologies, Mobility and Security*, pp. 1–5, Nov 2008.

[29] "Backhaul considerations for LTE and LTE-advanced," *Alcatel Lucent*, 2013.

[30] M. Mirahsan, R. Schoenen, H. Yanikomeroglu, G. Senarath, and N. Dung-Dao, "User-in-the-loop for hethetnets with backhaul capacity constraints," *IEEE Wireless Communications*, vol. 22, pp. 50–57, Oct 2015.

[31] "http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.html," in *Cisco Visual Networking Index Forecast and Methodology, 20152020*.

[32] L. Muscariello, D. Perino, and D. Rossi, "Do next generation networks need path diversity?," in *IEEE International Conference on Communications,*, pp. 1–6, Jun 2009.

[33] S. Ratnasamy, M. Handley, R. Karp, and S. Shenker, "Topologically-aware overlay construction and server selection," in *Proceedings.Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, pp. 1190–1199 vol.3, 2002.

[34] V. Nordell, A. Aurelius, A. Gavler, . Arvidsson, and M. Kihl, "Concurrency and locality of content demand," in *2013 International Conference on Smart Communications in Network Technologies (SaCoNeT)*, vol. 03, pp. 1–5, June 2013.

[35] D. Awduche, "RFC 3272," *IETF*, May 2002.

[36] S. Balon, F. Skivée, and G. Leduc, "How well do traffic engineering objective functions meet te requirements?," in *Proceedings of the 5th International IFIP-TC6 Confer-*

ence on Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communications Systems, NETWORKING'06, (Berlin, Heidelberg), pp. 75–86, Springer-Verlag, 2006.

[37] D. Awduche, J. Malcolm, J. Agogbua, M. O'Dell, and J. McManus, "Requirements for traffic engineering over MPLS," 1999.

[38] M. Kodialam and T. V. Lakshman, "Minimum interference routing with applications to mpls traffic engineering," in *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No.00CH37064)*, vol. 2, pp. 884–893 vol.2, 2000.

[39] A. Elwalid, C. Jin, S. Low, and I. Widjaja, "Mate: Mpls adaptive traffic engineering," in *Proceedings IEEE INFOCOM 2001. Conference on Computer Communications. Twentieth Annual Joint Conference of the IEEE Computer and Communications Society (Cat. No.01CH37213)*, vol. 3, pp. 1300–1309 vol.3, 2001.

[40] D. O. Awduche, "MPLS and traffic engineering in IP networks," *IEEE Communications Magazine*, vol. 37, pp. 42–47, Dec 1999.

[41] B. Fortz and M. Thorup, "Optimizing OSPF/IS-IS weights in a changing world," *IEEE Journal on Selected Areas in Communications*, vol. 20, pp. 756–767, May 2002.

[42] B. Fortz, J. Rexford, and M. Thorup, "Traffic engineering with traditional IP routing protocols," *IEEE Communications Magazine*, vol. 40, pp. 118–124, Oct 2002.

[43] B. Fortz and M. Thorup, "Internet traffic engineering by optimizing OSPF weights," in *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No.00CH37064)*, vol. 2, pp. 519–528 vol.2, 2000.

[44] R. Callon, "Use of OSI IS-IS for routing in TCP/IP and dual environments," Dec 1990, RFC 1195.

[45] “http://www.cisco.com/c/en/us/products/ios-nx-os-software/ios-netflow/index.html,” *Cisco IOS Netflow:*, 2002.

[46] A. Asgari, R. Egan, P. Trimintzios, and G. Pavlou, “Scalable monitoring support for resource management and service assurance,” *IEEE Network*, vol. 18, pp. 6–18, Nov 2004.

[47] Q. Ma, P. Steenkiste, and H. Zhang, “Routing high-bandwidth traffic in max-min fair share networks,” *SIGCOMM Comput. Commun. Rev.*, vol. 26, pp. 206–217, Aug. 1996.

[48] Z. Wang and J. Crowcroft, “Quality-of-service routing for supporting multimedia applications,” *IEEE J.Sel. A. Commun.*, vol. 14, pp. 1228–1234, sep 2006.

[49] J. L. Sobrinho, “Algebra and algorithms for qos path computation and hop-by-hop routing in the internet,” in *Proceedings IEEE INFOCOM 2001. Conference on Computer Communications. Twentieth Annual Joint Conference of the IEEE Computer and Communications Society (Cat. No.01CH37213)*, vol. 2, pp. 727–735 vol.2, 2001.

[50] N. Michael, A. Tang, and D. Xu, “Optimal link-state hop-by-hop routing,” in *2013 21st IEEE International Conference on Network Protocols (ICNP)*, pp. 1–10, Oct 2013.

[51] N. Michael and A. Tang, “Halo: Hop-by-hop adaptive link-state optimal routing,” *IEEE/ACM Transactions on Networking*, vol. 23, pp. 1862–1875, Dec 2015.

[52] A. Sridharan, R. Guerin, and C. Diot, “Achieving near-optimal traffic engineering solutions for current OSPF/IS-IS networks,” *Networking, IEEE/ACM Transactions on*, vol. 13, pp. 234–247, April 2005.

[53] K. Nemeth, A. Korosi, and G. Retvari, “Optimal OSPF traffic engineering using legacy Equal Cost Multipath load balancing,” in *IFIP Networking Conference*, pp. 1–9, May 2013.

[54] D. Xu, M. Chiang, and J. Rexford, "Link-state routing with hop-by-hop forwarding can achieve optimal traffic engineering," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, pp. –, April 2008.

[55] K. Xu, M. Shen, H. Liu, J. Liu, F. Li, and T. Li, "Achieving optimal traffic engineering using a generalized routing framework," *IEEE Transactions on Parallel and Distributed Systems*, vol. 27, pp. 51–65, Jan 2016.

[56] X. Ge, H. Cheng, M. Guizani, and T. Han, "5G wireless backhaul networks: challenges and research advances," *Network, IEEE*, vol. 28, pp. 6–11, Nov 2014.

[57] S. M. P. P.-E. A. R. P. Psenak, L. Nguyen, "Multi-topology routing in OSPF," *IETF*, p. RFC 4915 (2007).

[58] J. Wang, Y. Yang, L. Xiao, and K. Nahrstedt, "Edge-based traffic engineering for OSPF networks," *Computer Networks*, vol. 48, no. 4, pp. 605 – 625, 2005.

[59] A. Kvalbein, A. F. Hansen, T. Cicic, S. Gjessing, and O. Lysne, "Multiple routing configurations for fast IP network recovery," *IEEE/ACM Transactions on Networking*, vol. 17, pp. 473–486, April 2009.

[60] A. Jaron, M. Danel, P. Faucheux, A. Mihailovic, and A. Aghvami, "Qos-aware multi-plane routing for future IP-based access networks," in *IEEE Global Communications Conference*, pp. 2803–2808, Dec 2012.

[61] A. Kvalbein and O. Lysne, "How can multi-topology routing be used for intradomain traffic engineering?," in *Proceedings of the 2007 SIGCOMM Workshop on Internet Network Management*, INM '07, (New York, NY, USA), pp. 280–284, ACM, 2007.

[62] J. Zhang, K. Xi, and H. Chao, "Load balancing in IP Networks using generalized destination-based multipath routing," *IEEE/ACM Transactions on Networking*, vol. 23, pp. 1959–1969, Dec 2015.

[63] Z. Wang and J. Crowcroft, “Quality-of-service routing for supporting multimedia applications,” *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 1228–1234, Sep 1996.

[64] S. Chen and K. Nahrstedt, “An overview of quality of service routing for next-generation high-speed networks: problems and solutions,” *IEEE Network*, vol. 12, pp. 64–79, Nov 1998.

[65] R. Nagarajan and S. Ooghe, “Next-generation access network architectures for video, voice, interactive gaming, and other emerging applications: Challenges and directions,” *Bell Labs Technical Journal*, vol. 13, pp. 69–86, Spring 2008.

[66] S. Blake, D. Black, M. Carlson, Z. W. E. Davies, and W. Weiss, “Integrated services in the internet architecture: an overview,” *IETF*, p. RFC 2475, 1998.

[67] R. Braden, D. Clark, and S. Shenker, “Integrated services in the internet architecture: an overview,” *IETF*, p. RFC 1633, 1994.

[68] “http://www.cisco.com/c/en/us/products/ios-nx-os-software/integrated services/index.html,” in *Cisco Integrated Services*.

[69] “http://www.cisco.com/en/us/technologieswhitepaper09186a00800a3e2f.html,” in *Diff-Serv The Scalable End-to-End QoS Model*.

[70] K. Nichols, S. Blake, F. Baker, and D. Black, “Definition of the differentiated services field (DS Field) in the IPv4 and IPv6 headers,” *IETF*, p. RFC 2474, 1998.

[71] G. P. Fettweis, “The tactile internet: Applications and challenges,” *IEEE Vehicular Technology Magazine*, vol. 9, pp. 64–70, Mar. 2014.

[72] G. Fettweis and S. Alamouti, “5G: Personal mobile Internet beyond what cellular did to telephony,” *IEEE Communications Magazine*, vol. 52 ,Issue: 2, pp. 140–145, Feb. 2014.

[73] A. Aijaz, M. Dohler, A. H. Aghvami, V. Friderikos, and M. Frodigh, “Realizing the tactile internet: Haptic communications over next generation 5G cellular networks,” *IEEE WIRELESS COMMUNICATIONS*, Dec. 2015.

[74] ITU, “The tactile,” *ITU-T Technology Watch Report*, August 2014.

[75] N. Networks, “5G use cases and requirements,” *White paper*.

[76] M. Dohler and G. Fettweis, “The tactile internet IoT, 5G and cloud on steroids,” in *Telefonica Blog*, Oct. 2014.

[77] E. Steinbach, S. Hirche, M. Ernst, F. Brandi, R. Chaudhari, J. Kammerl, , and I. Vittorias, “Haptic communications,” *Proc. IEEE*, vol. 100, no. 4, p. 937956, Apr. 2012.

[78] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, “5G-enabled tactile internet,” *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 460–473, March 2016.

[79] N. Sakr, N. D. Georganas, J. Zhao, and X. Shen, “Motion and force prediction in haptic media,” in *2007 IEEE International Conference on Multimedia and Expo*, (Beijing), pp. 2242 – 2245, Nov. 2007.

[80] R. Wirz, M. Ferre, R. Marn, J. Barrio, J. M. Claver, and J. Ortego, “Telepresence across delayed networks: a combined prediction and compression approach,” in *2006 IEEE International Workshop on Haptic Audio Visual Environments and their Applications (HAVE 2006)*, (Ottawa, Ont.), pp. 171 – 175, Nov. 2006.

[81] T. H. Szymanski, “Securing the industrial-tactile internet of things with deterministic silicon photonics switches,” *IEEE Access*, vol. 4, pp. 8236–8249, 2016.

[82] D. Szabo, A. Gulyas, F. H. P. Fitzek, F. H. P. Fitzek, and D. E. Lucani, “Towards the tactile internet: Decreasing communication latency with network coding and software defined networking,” in *21th European Wireless Conference*, (Budapest, Hungary), pp. 1–6, May 2015.

[83] G. Zhang, T. Q. S. Quek, M. Kountouris, A. Huang, and H. Shan, "Fundamentals of heterogeneous backhaul design x2014;analysis and optimization," *IEEE Transactions on Communications*, vol. 64, pp. 876–889, Feb 2016.

[84] M. Fricke, A. Heckwolf, R. Herber, R. Nitsch, S. Schwarze, S. Vo, and S. Wevering, "Requirements of 4G-based mobile broadband on future transport networks," *Journal of Telecommunications and Information Technology*, Jan 2012.

[85] T. ii, "On basic properties of fault-tolerant multi-topology routing," *Computer Networks*, vol. 52, no. 18, pp. 3325 – 3341, 2008.

[86] X. Wang, S. Wang, and L. Li, "Robust traffic engineering using multi-topology routing," in *GLOBECOM 2009 - 2009 IEEE Global Telecommunications Conference*, pp. 1–6, Nov 2009.

[87] K. A. Woolston and S. L. Albin, "The design of centralized networks with reliability and availability constraints," *Computers Operations Research*, vol. 15, no. 3, pp. 207 – 217, 1988.

[88] I. Akgun, "New formulations for the hop-constrained minimum spanning tree problem via sherali and driscoll's tightened millertuckerzemlin constraints," *Computers Operations Research*, vol. 38, no. 1, pp. 277 – 286, 2011. Project Management and Scheduling.

[89] M. S. Monteiro, D. B. Fontes, and F. A. Fontes, "Hop-constrained tree shaped networks," *Foundation for Science and Technology*, 2012.

[90] M. Rebaiia and D. Ait-Kadi, "Network reliability evaluation and optimization : Methods , algorithms and software tools," *CIRRELT*, 2013.

[91] L. Gouveia and C. Requejo, "A new lagrangian relaxation approach for the hop-constrained minimum spanning tree problem," *European Journal of Operational Research*, vol. 132, no. 3, pp. 539–552, 2001.

[92] M. Monteiro, D. Fontes, and F. Fontes, “Hop-constrained tree shaped networks,” *Foundation for Science and Technology*, 2012.

[93] X. Ge, J. Ye, Y. Yang, and Q. Li, “User mobility evaluation for 5G small cell networks based on individual mobility model,” *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 528–541, March 2016.

[94] M. Frickea, A. Heckwolfa, R. Herberb, R. Nitschc, S. Schwarzed, S. Vod, and S. Weveringe, “Requirements of 4G-Based mobile broadband on future transport networks,,” *Journal of Telecommunications and Information Technology*, 2012.

[95] F. B. K. Nichols, S. Blake and D. Black, “Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 headers,” *RFC 2474*.

[96] A. Jaron, P. Pangalos, A. Mihailovic, and A.-H. Aghvami, “Proactive autonomic load uniformisation with mobility management for wireless internet protocol IP access networks,” *IET Networks*, vol. 1, pp. 229–238, 12 2012.

[97] H. Abrahamsson, B. Ahlgren, J. Alonso, A. Andersson, and P. Kreuger, “A multi-path routing algorithm for IP networks based on flow optimisation,” in *Proceedings of the 3rd International Conference on Quality of Future Internet Services and Internet Charging and QoS Technologies 2Nd International Conference on From QoS Provisioning to QoS Charging*, QofIS’02/ICQT’02, (Berlin, Heidelberg), pp. 135–144, Springer-Verlag, 2002.

[98] R. Hassin and A. Levin, “A better-than-greedy approximation algorithm for the minimum set cover problem,” *SIAM J. Comput.*, vol. 35, pp. 189–200, July 2005.

[99] H. N. Gabow and E. W. Myers, “Finding all spanning trees of directed and undirected graphs,” *SIAM Journal on Computing*, vol. 7, no. 3, pp. 280–287, 1978.

[100] G. Retvari and T. Cinkler, “Practical OSPF traffic engineering,” *Communications Letters, IEEE*, vol. 8, pp. 689–691, Nov 2004.

[101] U. Javed, M. Suchara, J. He, and J. Rexford, "Multipath protocol for delay-sensitive traffic," in *Communication Systems and Networks and Workshops. (COMSNETS)*, pp. 1–8, Jan 2009.

[102] D. P. Bertsekas, R. G. Gallager, and P. Humblet, *Data networks*, vol. 2. Prentice-Hall International New Jersey, 1992.

[103] M. S. R. Monteiro, D. B. M. M. Fontes, and F. A. C. C. Fontes, *Examining Robustness and Vulnerability of Networked Systems*. IOS, 2014.

[104] M. Rebaiaia, D. Kadi, and l. l. e. l. t. Centre interuniversitaire de recherche sur les réseaux d'entreprise, *Network Reliability Evaluation and Optimization: Methods, Algorithms and Software Tools*. IOS, 2013.

[105] M. Farhoudi, B. Abrishamchi, A. Mihailovic, and A. Aghvami, "Analysis of practical aspects of multi-plane routing-based load balancing approach for future link-state convergent all-IP access networks," *IEEE Transactions on Mobile Computing*, Aug 2017.

[106] R. Wirz, M. Ferre, R. Marn, J. Barrio, J. M. Claver, and J. Ortego, "Efficient transport protocol for networked haptics applications," in *6th International Conference, EuroHaptics 2008*, (Madrid, Spain), pp. 3–12, June 2008.

[107] G. Xue, W. Zhang, J. Tang, and K. Thulasiraman, "Polynomial time approximation algorithms for multi-constrained QoS routing," *IEEE/ACM Transactions on Networking*, vol. 16, pp. 656–669, June 2008.

[108] T. H. Szymanski, "Supporting consumer services in a deterministic industrial internet core network," *IEEE Communications Magazine*, vol. 54, pp. 110–117, June 2016.